DEPARTMENT OF DEFENSE

MILITARILY CRITICAL TECHNOLOGIES

PART III: DEVELOPING CRITICAL TECHNOLOGIES

SECTION 12: MANUFACTURING AND FABRICATION TECHNOLOGY

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SECTION 12.0—MANUFACTURING AND FABRICATION TECHNOLOGY

Scope

Highlights

- The continued development of rapid prototyping and near net-shape manufacturing will result in reduced costs, faster prototyping, and the ability to form a product closer to design (final product tailored to need).
- Higher speed machining capability means less time for the machining operation and, thus, reduced costs.
- The development and implementation of nanotechnology should result in improved military hardware.
- Quieter, longer lasting bearing assemblies will be used in submarines and helicopters.
- As manufactured dimensions become smaller, improved metrology equipment is necessary to maintain quality control and keep costs down.
- As manufactured dimensions become smaller and hardware becomes more expensive, more effective methods of in-process evaluation and non-destructive evaluation (NDE) are necessary to determine the quality of final product.
- Advanced land, sea, and air military robots will extend military capabilities in several areas, including reconnaissance and mine detection.

OVERVIEW

This section describes selected developing critical technologies for the production of U.S. military hardware. Such technology is important if the U.S. military is either to produce increasingly superior military performance or reduce the costs of existing hardware. In most cases, the technologies, the equipment, and the know-how are dual use and impact civil applications, where considerations of costs, agility, flexibility, competitiveness, and so forth have also become major concerns. All technologically advanced countries are pursuing similar programs if only to maintain a commercial advantage.

Several technologies included in subsection 12.1 are rather mature and are included as affordability issues. Affordability usually is considered in the context of a life-cycle allocation of resources. Major considerations for affordability include the following: (1) meets the consumer’s performance parameters; (2) has resources available; (3) is available when the consumer requires it; (4) can be maintained through its life cycle with or without hostilities and without undue shortages at projected budget levels; (5) has importance established compared with other requirements; and (6) reduces cost of operation; and (7) increases reliability, effectiveness, or efficiency.

The technologies addressed in this section either allow prototypes to be produced in a fraction of the time required by conventional methods or, in some cases, actually produce one-of-a kind parts, in a first-time-right concept, without the need of expensive stocks of spare parts. Other technologies (e.g., nanotechnology and several coating technologies) are aimed at effecting significant improvement in military hardware. Bearings (see subsection 12.2) addresses the development of three new types of bearings. In two of the technologies, the new bearings would be critical parts of the improved (high-speed) spindles used in machine tools. There is also the possibility that larger types might find application in quiet-running machinery (e.g., submarines). The remaining bearing development has potential application in electric power generation.

Developing technologies (see subsections 12.3 and 12.4) address techniques either to inspect dimensionally (metrology) the final product or test the final product for latent failures. Continued development of these technologies will result in more accurately produced and reliable products. Subsection 12.5 addresses production equipment. Technologies listed include both affordability issues (high-speed spindles, machine tool monitoring, and so forth) and technologies that might improve the overall capability of military hardware [hexapods, precision grinders, micromachines/microelectromechanical systems (MEMS), and so forth]. Subsection 12.6 discusses robots that might find increased use in actual battlefield applications.

In short, the items addressed in this section address two critical points: Can we make it better and can we make it more affordable?

RATIONALE

The U.S. military presently faces two challenges: One is well known, but the other is rather new. The former addresses the requirement to improve existing hardware and to develop newer, more advanced hardware. The latter addresses the need to accomplish both of the former requirements at reduced costs.

This section includes the various technologies used to manufacture not only military hardware but also a wide range of commercial hardware. The United States is not the world leader in all these technologies, and less technologically advanced countries are slowly improving their capabilities, by either purchasing advanced technologies or developing indigenous capabilities. As these advanced manufacturing technologies are proliferating throughout the world, the United States must continue to improve the technologies used to manufacture hardware, both from a military viewpoint and a commercial, competitive standpoint. At the same time, in a period of reduced military budgets, technologies must be developed to produce the hardware faster and at less cost.

BACKGROUND

For years, manufacturing and fabrication equipment has been a mainstay of industrial societies. This equipment was instrumental in bringing about the Industrial Revolution in the 18th century, the continued development of a wider range of machines in the 19th century, and the development of the concept of automation in the early 20th century. The mid-to-late 20th century witnessed a rapid expansion, with the introduction of automatic control of the machining axes and the incorporation of additional axes of motion. Indeed, one can trace the development of our present industrial society, as well as the sophistication of military hardware, to the development of manufacturing and fabrication equipment.

While rudimentary machines have been used throughout history, machines, as we know them today, were first developed in England and the United States. In England in 1775, J. Wilkinson invented a precision horizontal-boring machine to bore out cylinders for the newly invented steam engine. In the United States in 1798, Eli Whitney, invented machinery to produce interchangeable parts for the assembly of army muskets. The 19th century saw the development of milling machines and turning machines (for rifle stocks), gear-cutting machines, sewing machines, harvesters, grinding machines, and automatic screw machines.

The early 20th century witnessed the development of automation. This, coupled with the existing machines, opened the world to mass production. Products could now be manufactured in higher volume and at much lower cost, and the world experienced the mass-market appeal of automobiles and numerous other consumer products. Consumer products became affordable to a much wider range of the populations. At the same time, the military used this capability during World War II to produce tanks, planes, and ships in unprecedented numbers and at costs previously unheard of. Such machines were critical for the manufacture of engine parts and nuclear weapons.

However, automation alone was not sufficient to meet some of the post-World War II military needs, as more sophisticated weapons were developed. Production of these weapons required not only high accuracy, but also high repeatability. From this need came the development, in 1952, of a three-axis machine with the rudiments of numerical control (tape instructions). Development continued, with the introduction of automatic tool changing, four- and five-axes machines, and computer numerical controllers. Most subsequent improvements involved materials, better cutting tools, more accurate raceways, and faster and more stable spindle assemblies.

At the same time that these later developments were being introduced, composite materials were developed. To make best use of these new materials, new machines—tape-laying and filament-winding machines—were developed. This revolutionized the production of a wide range of commercial and military products (e.g., strong and lighter aircraft assemblies and automobile and tank parts).

Along with these continued improvements in manufacturing technology came continued requirements to perform both dimensional inspection and non-destructive inspection (NDI) of the final product.

The technology for coating various substrates has also experienced rapid growth and development during the 20th century. In earlier centuries, coatings were mainly applied for surface protection, and the most common media were paints or similar coatings. The perfection of equipment to produce vacuum environments increased rapidly the range of coating materials and technologies. Technologies moved from simple vacuum evaporation to chemical vapor deposition, plasma spraying, sputter deposition, ion implanting, and so forth. The refinement of these various technologies resulted in faster, more reliable jet aircraft (improved gas turbine engines); improved canopies for aircraft; longer-life bearings for applications in jet engines, machine tools, drive trains of automobiles, trucks, and tanks; specially designed dielectric layers and wear coatings for optical systems and sensors; and coatings to reduce low observability of weapon systems.

Other products addressed in this section, bearings and robotics, have experienced similar developments. While bearings, in their simplest concept, have been used for many years, it was not until the 19th century, with the introduction of machine tools, that they were recognized as individual, important components. In the mid 20th century, the development of tapered bearings, high-speed bearings, and miniature bearings were instrumental in improving automotive drive trains; high-speed machine tool spindles; and navigation systems and gyroscopes, respectively. Robots, as they are known today, have developed as a direct result of the invention of computers. They have matured from interesting playthings to important production tools in most state-of-the-art factories, whether as robotic welders or material delivery tools. In more sophisticated applications, they are used in nuclear facilities and are being developed as a battlefield replacement for soldiers in some dangerous environments. In addition, unmanned flying vehicles (robots) are receiving increasing attention as reconnaissance vehicles (including normal reconnaissance and as sensors for chemical or biological weapons).

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.0-1)

For most of the technologies included in this section, the United States is not the world leader but is a major player among other advanced technological countries. This is particularly true in manufacturing equipment, where Germany, Japan, and Switzerland are world leaders, either in the number of machines sold or the technical level of their machines. Advances in these technical areas (including bearings) are driven more by commercial needs than by military needs. Metrology and non-destructive testing have received considerable support from the European Union (EU) and, as a result, several European countries have active research programs in these areas. Japan is also very active.

The United States appears to have the unquestioned lead in battlefield robots. Other countries have developed robots more for industrial purposes [e.g., robotic welders and robots for space application (Japan)] or for use in the nuclear industry.

Country	Sec. 12.1 Advanced Fabrication and Processing	Sec. 12.1 Coating	Sec. 12.2 Bearings	Sec. 12.3 Metrology	Sec. 12.4 NDI and NDE	Sec. 12.5 Production Equipment	Sec. 12.6 Robotics
Argentina						●●	
Austria				●		●	
Australia	●			●		●	●●
Brazil	●					●●	
Canada	●●	●●		●●●	●●	●●	
Croatia			●				
Czech Republic	●●			●	●	●●	
China	●●	●		●●	●●	●●	
Denmark				●	●		
Finland		●	●	●			
France	●●●●	●●●	●●●		●●●	●●●	●●●
Germany	●●●	●●●●	●●●●	●●●●	●●●●	●●●●	●●●
Greece						●	
Hungary	●			●		●	
India						●	
Indonesia	●			●		●	
Israel	●	●		●●	●●	●●	●●
Italy	●●	●●	●	●●	●●	●●●	●●
Japan	●●●●	●●●●	●●●	●●●●	●●●	●●●●	●●
Korea			●		●	●	
Netherlands	●	●●●	●	●●●	●●●	●●	
Norway						●	
Romania	●			●		●	
Russia	●●	●	●	●●	●●●	●●●	●●
Singapore					●	●	●
Spain				●●	●●	●●	
Sweden	●●	●		●	●●	●●	
Switzerland	●●	●●●	●●●	●●●	●●●	●●●	
Taiwan	●			●●		●●	
Ukraine		●●				●	
UK	●●●●	●●●	●	●●●	●●●●	●●●	●●●
United States	●●●●	●●●●	●●●●	●●●●	●●●●	●●●●	●●●●

Legend:

Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.0-1. Manufacturing and Fabrication Technology WTA Summary

12.1—ADVANCED FABRICATION AND PROCESSING

Highlights

- Rapid prototyping and near net-shape manufacturing will result in reduced cost of producing prototypes and end products.
- More accurate grinding machines will result in reduced cost and improved engine performance.
- Breakthroughs in nanotechnology will result in significant improvements in electronics, chemistry, and materials, with widespread military applications.
- Continued advances in coating technologies will result in improved hardness capability of various military hardware surfaces and improved performance in multiple domains.

OVERVIEW

This subsection covers two groups of technologies. The first includes equipment for fabricating structures using a wide range of different equipment, ranging from various thermal furnaces and equipment for bending, stretching, or rolling material to form-desired shapes to scanning tunneling microscopes (STMs). The second group includes the development, refinement, and production of nonorganic coatings on non-electronic substrates. Such substrates include ceramics, low-thermal-expansion glass, metals, polymers, and so forth. Coating materials include ceramics, metals, dielectric layers, abradable materials, and so forth. The coating procedures include chemical vapor deposition (CVD), various techniques of physical vapor deposition (PVD), sputter deposition, plasma spraying, and ion implantation.

Many of the developing technologies associated with the fabrication equipment involves new and continuing procedures to produce what is needed accurately and affordably. While manufacturing most products, prototypes have to be produced. An ongoing program, rapid (virtual) prototyping allows for a quick three-dimensional (3-D) fabrication of the prototype so that a design can be evaluated before production is initiated. This technology consists of:

- A computer-aided design (CAD)-generated virtual-reality model of the design, which can be analyzed and altered, as necessary
- The ability to perform virtual machining (manufacturing) of the virtual part, followed by a computer comparison of the virtual part with the original digital design
- The capability to produce a model from the pattern in a fraction of the time required to produce a model using conventional model-shop procedures.

Additional effort is being aimed toward extending this procedure to produce not only prototypes, but also final products, thus significantly reducing the time/cost of production.

Rapid prototyping is an integral part of the product realization cycle. It permits the fabrication of complex parts in a fraction of the time required by traditional prototyping techniques and, thus, will play a significant role in making products more affordable. Rapid prototyping can be categorized into two areas: virtual and physical. In the former, the computer system (CAD) is used to generate a 3-D image that can be analyzed before final manufacture. In the latter, the CAD program is fed directly to the manufacturing tool that produces either a final product (most often made of ceramic, wax, or plastic) or a mold to produce a metal object. Much effort is being expended to produce high-quality metal objects without the need of a mold.

Another ongoing developing technology included in this section is near net-shape. Near net-shape is an ongoing program with the goal of lowering the costs of manufactured products by reducing the amount of raw material used (less waste) and by producing a product so close to the design shape that only a minimum amount of subsequent machining is required to achieve the desired final shape. Casting is an example of a technology in which much effort is being expended in near net-shape. The traditional trial-and-error approach of selecting an optimum combination of design and process parameters results in long lead times and excessive material waste. To circumvent this approach, computer simulation of the casting process is being used and evaluated as a means to ensure that defect-free castings are produced in the first attempt.

Generally, items manufactured using techniques such as casting, injection molding, hot isostatic pressing, and so forth result in a final shape different from the shape of the container. As a result, historically, many products were manufactured using several steps until the proper shape of the container could be determined. Near net-shape technology uses CAD programs to calculate the resultant changes in shape that occur during cooling of the product so that the final product is "near the designed shape." This is of particular importance when fabricating ceramic parts because such items are very hard and subsequent finishing steps can be quite time consuming and expensive. Near net-shape is an approach similar to the philosophy of "first-time-right" manufacturing.

Ausforming is another developing near net-shape technology to manufacture superior spur and helical gears at less cost. It involves contour austenization of case-hardened gear teeth and quenching to metastable austenite, followed by plastic deformation of the gear tooth surface layers to final dimensions and then quenching to marstenite. The potential advantage of this procedure is that it forms the final shape of the gear without damaging the hard surface. It eliminates the need for gear tooth grinding while improving surface durability and fatigue behavior and reducing overall processing time and costs. The objective of the research program is to produce gears of better than 12 American Gear Manufacturing Association (AGMA) quality.

Semi-solid metalworking (SSM) is another example of near net-shape manufacturing, incorporating elements of casting and forming. In this process, the raw material is melted and allowed to cool to form a "mush" of liquid/solid material. This slush is then forced into a die, forming a final product that has higher structural integrity than castings but can be produced at lower cost than forgings.

Parts produced with SSM enjoy several advantages:

- Have higher structural integrity than castings, yet can be produced at lower cost than forgings
- Are less porous than parts produced with conventional high-pressure die casting
- Have equivalent properties to parts produced by either forging or conventional machining but require fewer steps.

To date, SSM has been demonstrated with aluminum, titanium, and copper; however, its implementation in either civil or military applications has been hindered by lack of process specifications, process models, training, and experience.

The most radical technology in this section deals with nanotechnology, defined as an anticipated manufacturing technology giving thorough, inexpensive control of the structure of matter (i.e., the ability to design and manufacture devices that are only tens or hundreds of atoms across). Nanotechnology is still an emerging technology. Significant advances have been made (e.g., buckyballs and fullerenes), but there has been little commercial activity. Sandia National Laboratories has reported the development of "supersensitive coating to improve detection of dangerous materials," and some use has been made of conducting fullerton as a filler material in plastics to make the plastic conductive. However, nanotechnology holds promise of an industrial revolution, as witnessed by the organizations—both government and industry—that are active in research. At a recent government nanotechnology workshop, agencies in attendance included the National Science Foundation (NSF), Department of Defense (DoD) (many organizations), DOC, National Institute of Standards and Technology (NIST), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), and DOE.

Most of the research technology areas include materials, electronics, and medical devices. In materials, the bulk behavior of materials can be dramatically altered when constituted from nanoscale building blocks, the hardness and strength of nanophase metals can be greatly increased, and nanophase fillers in composite materials yield unique properties. Buckyballs and fullerenes (sometimes called buckytubes) are examples of nanophase materials. They are specific forms of carbon that are one-fourth the weight of steel and greater than 100 times stronger. Such capabilities hold great promise not only for use as improved cables, but as filler material for composite materials. Other potential applications include metal-doped buckytubes that theoretically would be 50 times more conductive than copper. Such tubes would bring about a revolution in power transmission.

Such a capability holds great promise in biology, electronics, chemical catalysis, and materials. This technology requires the capability to manipulate microscopic atoms, molecules, and so forth to form the desired structures. The procedures used in nanobiotechnology might be significantly different from those used in nonbiological applications. In the former, researchers are studying the molecular behavior of nucleic acids and proteins. In the latter, researchers are actively studying ways to use “buckyballs” and “buckytubes” (nanotubes) to produce usable end-items. Some military applications of this technology include biosensors, stronger ceramics and composites, superior coatings, abrasion-resistant materials, and so forth.

Buckyball structures are extremely malleable, can be compressed to less than half their original volume, and can be joined readily to other atoms, creating new capabilities. Although there have been no practical applications, as yet, for buckyballs, possible applications include superior armor, superconductor applications, ferromagnetic applications, superior lubricants, and medical applications.

Another fallout from buckyballs, and possibly more promising, are buckytubes (or nanotubes). These nanotubes are similar to buckyballs, but, instead of a sphere, the carbon atoms are linked together in a chicken-wire pattern. In certain cases (controllable), the carbon sheets roll together, and the edges join seamlessly, forming a nanotube. In some arrangements, the tube is a conductor. In other arrangements, the tube is a semiconductor. If two such tubes are joined to form a single molecule, the junction acts like a diode. Other possibilities for nanotubes include use as ultrastrong, thin cable and as a means of delivering medicine internally. Presently, conductive nanotubes are used in plastics to make the plastic conductive.

Coating technologies include several programs of developing technologies. Research has been conducted for several years on the technology for the deposition of diamond coatings. While some success has been achieved, the widespread application of the technology is still 5 to 10 years away. Nanophase coatings and cubic boron nitride coatings are more recent research programs, and both offer potential in the same technology area as diamond coatings—extremely hard, durable coatings. All these technologies have wide potential applications in military and civil applications. Of the three, nanophase coatings (related to nanophase materials) is probably the most esoteric.

Items fabricated from nanophase materials have superior characteristics. For example, nanophase copper and palladium have hardness and yield strengths 500 percent greater than conventionally produced metal, and nanophase ceramic material can be manufactured with much greater ductility than conventionally manufactured ceramics. These same bulk-nanophase characteristics result in similar improvements in the characteristics of nanophase coatings, particularly in applications requiring improved wear-resistant surfaces and increased thermal protection.

More recent studies have focused on the use of multilaser sources to heat the surface of a substrate selectively—resulting in extremely hard, graded surfaces. The technology can be modified by adding specific constituents to the plasma around the surface, altering the surface layer of the substrate and resulting in an extremely hard surface alloy.

RATIONALE

The fabrication equipment and technologies have significant military application. Along with machine tools (see subsection 12.5), these technologies form the cornerstone for producing mechanical hardware; composite sections for military aircraft, ships, and land vehicles; and various engine and transmission parts. The coating technologies included here address new technologies to improve the high-temperature operation or corrosion resistance of the base materials, or to effect changes in the optical characteristics of the substrate, and so forth.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.1-1)

Advanced manufacturing techniques are present, in varying degrees, throughout the industrial world. However, the main countries using these techniques are France, Germany, Japan, the United Kingdom, and the United States. In the United States, these efforts are supported by DoD and NSF, with considerable effort by industry and universities. In Europe, the European Commission has funded studies in several companies, and other companies are quite active. These advanced manufacturing techniques include several technologies that are primarily aimed at shortening turn-around time and reducing costs of final product.

Coating technologies research is primarily aimed at improving some aspect of hardware operation, whether it be improved hardness, resistance to corrosion, or improved thermal protection.

Country	Advanced Fabrication and Processing	Coating
Brazil	●	
China	●●	●
France	●●●●	●●●
Germany	●●●	●●●●
Hungary	●	
Indonesia	●	
Israel	●	●
Italy	●●	●●
Japan	●●●●	●●●●
Netherlands	●	●●●
Romania	●	
Russia	●●	●
Sweden	●●	●
Switzerland	●●	●●●
Taiwan	●	
Ukraine		●●
UK	●●●●	●●●
United States	●●●●	●●●●

Legend:

Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.1-1. Advanced Fabrication and Processing WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
12.1. ADVANCED FABRICATION AND PROCESSING

DATA SHEET 12.1. RAPID PROTOTYPING MANUFACTURING (RPM)

Developing Critical Technology Parameter	Some early users of this technology report time reductions of 5 to 1 and cost reductions of 10 to 1. This is an ongoing program in a wide range of civil and military facilities.
Critical Materials	The materials depends on the RPM procedure used, including materials such as photopolymer epoxy resins, acrylates, polycarbonates, nylon, elastomers, certain metals, thermoplastics, polyester, ceramic powder, and so forth.
Unique Test, Production, Inspection Equipment	Laser stereolithography, laser sintering equipment, polymer extrusion equipment, and computers (for CAD).
Unique Software	CAD programs.
Technical Issues	Decision on whether to fabricate models or final end product. Ability to convert system to produce metal product.
Major Commercial Applications	Aerospace products that are produced in small volume and moulds for items produced in large volume (e.g., automotive).
Affordability	1. Allows quick fabrication of 3-D prototypes to evaluate of the design before beginning production. 2. Allows rapid production of small-volume products, spare parts, and so forth.

RATIONALE

An affordability issue. Potential applications of RPM include the manufacture of dies and molds, the fabrication of 3-D prototypes to allow evaluation of the design before beginning production and, eventually, the fabrication of low-volume final product. In today's marketplace, whether military or commercial, the time-to-market for new products is becoming increasingly critical. To reduce this time, all phases of design and development must be compressed. Rapid prototyping aids this process.

RPM can exist solely as a virtual representation of a product (CAD design) so that designers can determine the interface between several virtual objects before the final manufacture of the product. It is also used to produce prototypes of the final product to determine how the shape operates in some environment (e.g., a model to be studied in a wind tunnel). Continued development of the technology should result in the ability to produce a final product on a one-at-a-time basis, particularly after the technique to produce metal and composite structures matures. This should have a particular benefit for the manufacture of low-volume parts, as required for many military applications. It could also play a part in reducing the need for extensive spare part inventories if replacement parts could be produced in a matter of hours.

Efforts to improve this technology are being carried out worldwide as the pressure to reduce costs—for military and commercial applications—continues.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●	France	●●●	Germany	●●●●	Israel	●
Japan	●●●●	Russia	●	UK	●●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in rapid prototyping is present, in varying degrees, throughout the industrial world. However, the main countries involved in this research are the United States, Germany, Japan, and France. Lesser activity is present in Canada, Israel, Russia, and the United Kingdom.

In the United States, government, industry and universities carry out research. These organizations include NASA, Los Alamos National Laboratories, Sandia National Laboratories, Stanford University, Carnegie Mellon University, the University of Texas, Clemson University, the University of Maryland, 3-D Systems, Cubital, Stratasys, Inc., Helisys, and Alcoa.

In Europe, the following are examples of organizations have active RPM programs: Fraunhofer IPT, Rhine-Westphalian Casting Institute, Max Planck Institute, Karlsruhe University, Volkswagen, Schneider Engineering, and Wolff Engineering in Germany; the LeMans Center, CREATE, CIRTES, Aerospatiale, SNECMA, and Peugeot in France; and the University of Sunderland, Cranfield University, Laser Prototypes, Ltd., and Rover in the United Kingdom.

In Asia the following organizations have active RPM programs: Tohoku University, Osaka University, Nagoya University, Komatsu, Hitachi, Honda, Denkin Engineering, Mitsubishi, and Sony in Japan.

DATA SHEET 12.1. IMPROVED NEAR NET-SHAPE

Developing Critical Technology Parameter	This is a continuing, ongoing program, encompassing several different manufacturing technologies. Near net-shape manufacturing is a manufacturing process aimed at producing a final product that closely approximates the final design shape. Advanced simulation software is an important element is most of the processes. As an example, “Ausforming,” a technique being developed for gear manufacture, minimizes manufacturing steps, preserves the hard surface of the gear, and imparts compressive residual stress into the gear. The technical objective is to produce gears of that are greater than 12 AGMA quality. The goals of near net-shape manufacturing are cost reduction (less final machining to reach the final design shape and less waste) and improved technical characteristics of the final product.
Critical Materials	Depends on the process used. Fine powder technologies (metal and ceramic).
Unique Test, Production, Inspection Equipment	Hot isostatic press, powder press, casting equipment, injection molding equipment, X-ray machines, electron microscopes, metallography, forming press, and so forth.
Unique Software	CAD for process simulations. To incorporate algorithms to initiate changes in component form because of compensation for shrinkage, warpage, or other process and material conditions.
Technical Issues	The specific near net-shape process used (e.g., casting, forging, and so forth), the degree of approximation of the final product to the design, the technique used, and the need to produce lower cost fine powders.
Major Commercial Applications	Aerospace engines; automotive transmission cases and engine blocks; marine engine blocks and motor mounts; bearings made from powder metallurgy; home appliances (e.g., washers, dryers, and mixers); and office equipment (e.g., printer heads and disc drives); and so forth.
Affordability	If items can be cast, or prepared, closer to their final shape, fewer machining operations are required to reach the design shape, thus reducing cost.

RATIONALE

Both an affordability issue and a technology issue:

- If items can be cast, or prepared, closer to their final shape, fewer machining operations are required to reach the design shape.
- As the technology matures, dies and molds should be made at a low enough cost that they could be discarded after approximately a half dozen uses and new ones could be used (more of a mint-final product).
- This process produces less waste than more conventional processes in which more material must be machined or ground away. This would be valuable to proliferants who have a scarcity of raw materials.
- The final product is often superior in technical parameters and has a higher yield.

Products manufactured with this technology are used in most military hardware, from helicopters to submarines to jet engines.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●●	Japan	●●●	Russia	●
UK	●●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

With increased worldwide emphasis on reducing the cost of manufactured products, research in near net-shape manufacturing is widespread throughout the industrial world. This is particularly true in the United States, Germany, France, Japan, and the United Kingdom.

In the United States, government, industry, and universities carry out research. These organizations include the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB), Lawrence Livermore National Laboratory (LLNL), the National Centers of Excellence at Johnstown, Sandia National Laboratories, Consolidated Technologies, Fraunhofer, USA, GE CRD, Lockheed Martin Vought Systems, Penn State College (ausforming), and the Massachusetts Institute of Technology (MIT).

In Europe, several organizations in different countries have active near net-shape programs: the Fraunhofer Institute for Applied Materials Research, the Max Planck Institute, IFW-Dresden, University of Erlangen, Daimler-Benz, BMW, Adam Opel, and Buck GmbH in Germany; the Association pour la Recherche et le Developmente des Methods et Processus Industriales, Ecole des Mines de Paris, Renault, Peugeot, and Citroen in France; Oxford University, Nottingham University, Birmingham University, Jaguar Cars, Ltd., and Bohler-Uddeholm, Ltd., in the United Kingdom. The Institute for Metals Superplasticity Problems (Uffa) in Russia is also active.

In Asia, the following organizations have active programs: the University of Tokyo, Mitsubishi Research Institute, Intermetallics Company, Ltd., Mitsui Engineering, NHK Spring R&D Institute, and the Mitsubishi Kasei Corporation in Japan and the National University of Singapore in Singapore.

DATA SHEET 12.1. SEMI-SOLID METALWORKING (SSM)

Developing Critical Technology Parameter	This technology offers the potential of significantly reducing the cost of titanium parts (particularly those for shipboard use). Initial studies indicate that parts manufactured using SSM have higher structural integrity than castings and are less expensive than forgings.
Critical Materials	The base materials used in the manufacture of end product.
Unique Test, Production, Inspection Equipment	Casting and forming equipment, X-ray machines, electron microscopes, metallography, and so forth.
Unique Software	CAD and process simulation software.
Technical Issues	The widespread application of SSM has been hindered by the lack of process specifications and process models.
Major Commercial Applications	Aerospace engines; automotive transmission cases and engine blocks; marine engine blocks and motor mounts; home appliances (e.g., washers, dryers, and mixers); and office equipment (e.g., printer heads and disc drives); and so forth.
Affordability	Pilot work with titanium valves for naval underwater applications have been successful, and estimates indicate that cost savings per valve will be in the $1K to $10K range. If this technology allows conversion to titanium valves, savings could reach $13,000,000 per ship, over a 40-year life.

RATIONALE

SSM technology is a near net-shape approach to manufacturing wherein the metal, in a semi-solid state (i.e., at a temperature between its solid and liquid states) is formed, using pressure, in dies. This combination of slush and pressure results in a final product with less voids. More conventional processing uses either molten metal (casting) or solid metal (forming). Parts produced by SSM have higher structural integrity than castings and can be produced at lower costs than forgings. The process is capable of producing parts that are essentially free of the porosity associated with conventional high-pressure die casting. At the present time, SSM is being used with titanium and aluminum.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	Germany	●	Japan	●●	Norway	●
Switzerland	●	UK	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

While SSM research is worldwide, it is not as extensive as in some other technology areas. Principal effort is in the United States, Germany, Norway, and Switzerland.

In the United States, the principal organizations active in SSM are MIT, Worcester Polytechnic Institute, Cornell University, Drexel University, Oak Ridge National Laboratory (ORNL), Consolidated Technologies (NCEMT), Aluminum Company of America, Northwest Aluminum, Ormet Corporation, Reynolds Metals, and Failure Analysis Associates.

In Europe, organizations with research in this area are the University of Vienna in Austria; the EFU Gesellschaft for Ur/Umformtechnik in Germany; the Norwegian Institute of Technology in Norway; the Göteborg University in Sweden; the Eidgenössisches Technische Hochschule (ETH)-Zurich, and Buhler Incorporated in Switzerland; and the University of Sussex in the United Kingdom.

DATA SHEET 12.1. TECHNOLOGY FOR MOLECULAR MANUFACTURING (NANOTECHNOLOGY)

Developing Critical Technology Parameter	The manufacture of military items using extremely small and/or extremely strong building materials [e.g., buckyballs (fullerenes), buckytubes (nanotubes), and so forth]. Nanophase materials and nanocomposites are characterized by ultra-fine grain size (< 50 nm). Products manufactured from such materials have the potential of possessing superior mechanical and electrical properties (e.g., higher ductility at elevated temperatures, increased hardness of wear-resistant coatings, higher strength materials, optoelectronic devices, and so forth).
Critical Materials	The base materials used in the manufacture of end product. Buckyballs and nanotubes are made of carbon. Many potential applications of buckyballs and nanotubes would require the addition of other elements to the carbon structure. This could include hydrogen or fluorine atoms to form “fuzzy” balls, potassium to form a superconducting material, and so forth.
Unique Test, Production, Inspection Equipment	Scanning tunneling microscopes (STMs) for the manipulation of atoms and furnaces to form buckyballs and nanotubes.
Unique Software	None identified.
Technical Issues	The ability to form nano-sized molecules and to form them into final shape still limits the advancement of the technology. The present cost of producing both buckyballs and nanotubes also limits the rapid development of the technology.
Major Commercial Applications	Applications could include very small, highly sophisticated, low-power electronic systems; stronger, lighter structural members; multifunctional surfaces; small, accurate antennas; and so forth.
Affordability	Not an affordability issue.

RATIONALE

Nanotechnology was defined by Drexler as “the knowledge and means for designing, fabricating, and employing molecular scale devices by the manipulation and placement of individual atoms and molecules with precision on the atomic scale.” This so-called “bottom-up” approach to manufacture contrasts sharply with the conventional “top-down” approach, where a bulk material is machined down to meet the designed shape. For the electronic applications of nanotechnology (nanoelectronics), see Section 8.6.

The specific military applications of this technology are not clear. However, the following capabilities could result from this technology: superior armor; advanced lubricants; extremely small, extremely fast computers (ability to control strategic operations at very high speeds with low power consumption); lighter and stronger structural members; biosensors; abrasive-resistant materials; and so forth. Reportedly, the Defense Advanced Research Projects Agency (DARPA), NASA, and the NSF are supporting research in ultra-dense, ultra-fast computing elements (DARPA); fast computers, strong and light materials, and active and self-repairing materials (NASA); and synthesis/fabrication of nanostructures, processing of molecules into functional nanostructures, and the fundamental physical, chemical and biological properties of nanostructures (NSF).

Research on specific characteristics of buckyballs and nanotubes have demonstrated that:

- They are unaffected by collisions at speeds of up to 15,000 mph.
- When compressed, they are harder than diamonds.
- Their internal cavity is large enough to hold any known element, thus having the possibility of being a carrier for medicines or radioactive materials.

- The addition of hydrogen or fluorine atoms to each of the carbon atoms ("fuzzy balls") should result in films with very low coefficient of friction.
- The addition of potassium atoms can result in either a superconducting material or an insulator, depending on the number of potassium atoms.
- Nanotubes could be used as fibers in composite materials, resulting in materials superior to carbon-carbon composite materials.

Most of these characteristics can be related to superior military hardware. The resiliency might be of value in rocket fuels or improved personnel armor. The compressibility could lead to improved shock absorbers. The use of nanotubes in composite materials could result in superior aircraft or other vehicle body structures. Improved lubricants have innumerable applications, ranging from engine parts and submarine gear systems to advanced gyroscopes.

Figures 12.1-2 and 12.1-3 are computer representations of a buckyball (fullerene) and a nanotube.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	France	●●	Germany	●●●●	Italy	●●
Japan	●●●●	Sweden	●	Switzerland	●●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in nanotechnology—particularly in buckyballs and nanotubes—is present, in varying degrees, throughout the industrial world. However, the main countries involved in the research are the United States, Germany, Japan, the United Kingdom, France, Switzerland, Austria, and Sweden.

In the United States, government, industry, and universities carry out research. These organizations include ORNL, the Naval Research Laboratory (NRL), Institute for Molecular Manufacturing, Foresight Institute, Lucent Technologies, Xerox, Dupont de Nemours, State University of New York (SUNY)-Stoneybrook, MIT, Boston University, Widener University, New York University, Arizona State University, Northwestern, University, the University of Southern California, and the California Institute of Technology (Caltech).

In Europe, organizations with research in this area include the following: the Max Planck Institute, Stuttgart, IFW, Dresden, MBI, Berlin, the Institute für Festkörper and Werk, the Technische Universität Berlin, the Humboldt University, the University of Freiburg, and the University of Munich in Germany; Sussex University, Cambridge University, Birmingham University, Nottingham University, Cranfield University, the New Chemistry Lab, and the Institute of Bioscience and Technology in the United Kingdom; IBM, the University of Basel, and ETH-Zurich in Switzerland; the University of Vienna in Austria; Göteborg University in Sweden; and the Fondazione ELBA, the University of Genova, the University of Bologna, the University of Firenze, and the University of Milano in Italy.

In Asia, organizations with research in this area include the following: NEC Corporation, Riken Institute, IIE, Hitachi Basic Research Laboratory, NTT, Fujitsu Limited, Mitsubishi Materials Corporation, Hamamatsu Photonics, Sony Corporation, Toshiba Corporation, the University of Tohoku, and the University of Tokyo in Japan.

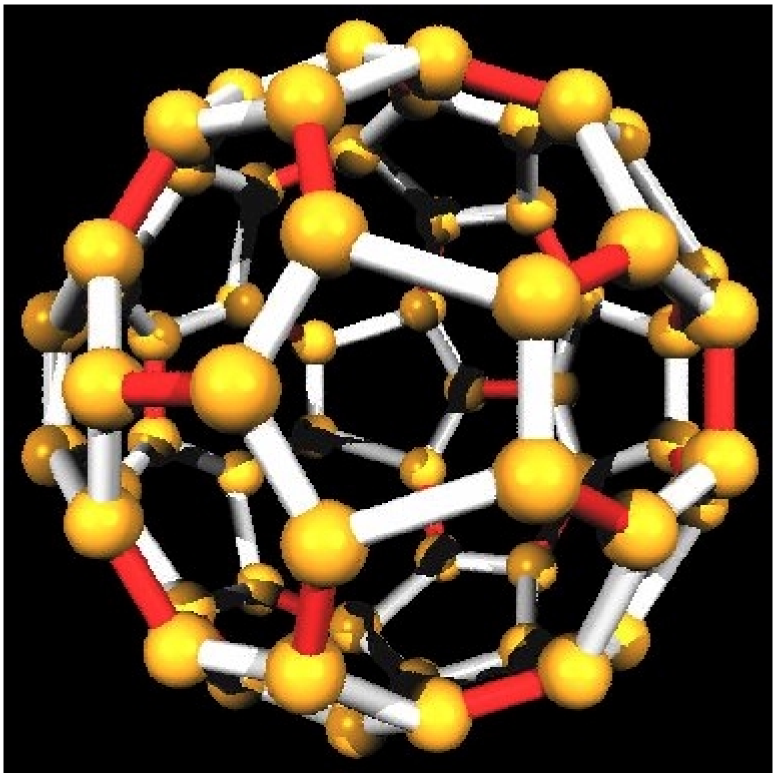


Figure 12.1-2. Buckyball (Fullerene)

Note for Figure 12.1-2: *This figure shows the C_{60} structure of the 60 symmetrically arranged carbon atoms.*

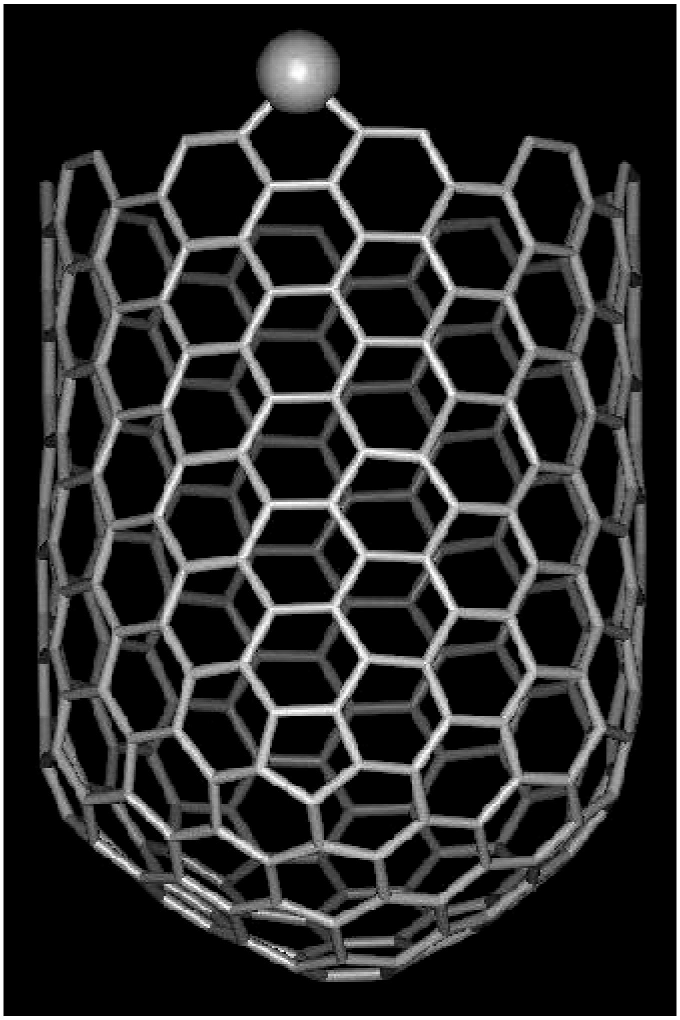


Figure 12.1-3. Nanotube

Note for Figure 12.1-3: *Computer simulation demonstrates the nanotube structure, a thin hollow cylinder of carbon capped at each end.*

DATA SHEET 12.1. TECHNOLOGY FOR DIAMOND COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings. Characteristics should approach the following properties of diamond: • Hardness of 80–90 GPa • Coefficient of thermal expansion (at room temperature) of 0.8×10^{-6} K • Coefficients of 0.005 • Thermal conductivity (at room temperature) of 2×10^{3} W/m/K • Very resistant to chemical corrosion • Biologically compatible.
Critical Materials	Carbon deposition source.
Unique Test, Production, Inspection Equipment	Chemical vapor-deposition equipment, sputtering, ion beam and direct current (DC) plasma deposition equipment, multi-laser system. Scanning electron microscopes (SEMs) and various optical equipment to analyze the surface.
Unique Software	None identified.
Technical Issues	Major concerns are (1) difficulty in obtaining smooth films for potential applications in optics and thermal management, (2) need to increase growth rates while not negatively affecting surface quality, (3) development of a lower temperature deposition requirement.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion.
Affordability	Not an affordability issue.

RATIONALE

Diamond coatings offer extremely hard, durable, transparent coatings for a wide variety of applications. Extensive research is being conducted worldwide, and progress is continuing. Some applications have entered the commercial marketplace [e.g., coating of cutting tools (not applicable for machining ferrous materials) and heat sinks]. Most of the applications with direct military application are primarily in the research or development stage. This includes wear/corrosion coatings for infrared (IR) sensors (weapon systems), nose cones and domes, fibers for the manufacture of improved composite materials, and optical fibers for improved telecommunications. Improved tribological characteristics, coupled with improved wear, could significantly improve such items as bearings and raceways, and engine parts.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●●●	Belgium	●	China	●	Finland	●
France	●●●	Germany	●●●●	Japan	●●●	Korea	●●
Switzerland	●●●	UK	●●●	United States	●●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Much of the industrialized world is conducting extensive research in diamond coatings. The major research is being done in the United States, Germany, and the United Kingdom. The European “Consortium for Superhard

Materials” includes 33 German, 5 Austrian, and 7 Swiss universities. Because of the large number of universities and organizations involved in diamond coating research, only a representative sample will be listed.

In the United States, organizations conducting this research include NRL, Argonne National Laboratories, NASA-Lewis, Case Western Reserve, the University of California-Berkeley, Rice University, the University of Wisconsin, Vanderbilt University, the University of Florida, Diamonex, Xerox, Crystalline Materials Corporation, Lockheed, and QQC Technology.

In Europe, organizations pursuing this research include the following: the University of Wuppertal, the University of Hamburg, the University of Bonn, the University of Kassel, the University of Erlangen, the Technical Universities of Berlin and Chemnitz, Daimler-Benz, and the Fraunhofer Institute in Germany; the University of Nancy, Balzers SA, and the Centre Technique des Industries Mechaniques (CETIM) in France; DRA, Bristol University, Harriot-Watt University, Kings College, University College London, and the University of Glasgow in the United Kingdom; the University of Vienna in Austria; the Centre Suisse d’Electronique CSEM, the Ecole Polytechnique Federale de Lausanne, and the Universities of Neuchatel, Basel, Fribourg, and Bern in Switzerland; the Linburgs Universitair Centrum in Belgium; and the University of Helsinki in Finland.

In Asia, Japan is most active, with the National Institute for Research in Inorganic Materials (NIRIM), Osaka University, Mitsubishi Materials, Sumitomo Electric, and Kobe Steel Research having extensive programs. Other Asian efforts exist at the Korea Institute of Science and Technology and the Industrial Technology Research Institute in Korea and the Center of Super-Diamond and Advanced Films in Hong Kong (China).

DATA SHEET 12.1. TECHNOLOGY FOR NANOPHASE COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings and thermal barrier coatings produced from the deposition of particles whose size is in the nanometer range (10^{-9} m).
Critical Materials	Many different materials are being studied (e.g., n-WC/Co, MnO_2, yttria-stabilized zirconia, SiC, BN, and so forth).
Unique Test, Production, Inspection Equipment	Thermal spray equipment, CVD equipment, DC plasma deposition equipment, PVD equipment, and equipment to analyze the surface coating.
Unique Software	None identified.
Technical Issues	Difficulty in forming nano-sized particles for source material.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion or high temperatures. Applications would extend to cutting tools, engines, sensor windows, and so forth.
Affordability	Not an affordability issue.

RATIONALE

Nanophase coatings enable increased wear, heat transfer and corrosion resistance, fatigue strength and fracture toughness compared with similar coatings using larger size particles. They offer extremely hard, durable coatings for a wide variety of applications, ranging from engine parts to composite fibers. Thermal barrier coatings are critical in engine technology, allowing operation at higher temperatures.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	France	●●●	Germany	●●●	Japan	●●●
Sweden	●	Switzerland	●	Ukraine	●●	UK	●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in nanotechnology—particularly in buckyballs and nanotubes—is present, in varying degrees, throughout the industrial world. However, the main countries involved in this research are the United States, Germany, France, Japan, Austria, Sweden, Switzerland, and the United Kingdom.

In the United States, government, industry, and universities carry out research. These organizations include NIST, Edwards Air Force Base, ORNL, NRL, Argonne National Laboratories, Rice University, Widener University, Rutgers University, University of California (Irvine), the University of Minnesota, Drexel University, MIT, SUNY-Stoneybrook, Stevens Institute of Technology, Dupont de Nemours, Inframat Corporation, Englehard Corporation, Manpower Enterprises, Inc., Science Applications, Inc., and Integrated Systems Analysts.

In Europe, the following organizations have active research programs: the Centre de Recherches sur les Tres Basses Temperature, Grenoble, and the Universitaires Notre Dame de la Paix, Namur in France; the Max Planck Institute für Metallforschung, MBI, Berlin, the Fraunhofer Institute for Applied Materials Research, and the Technical Universities of Berlin and Darmstadt in Germany; the University of Vienna in Austria; the Göteborg University in Sweden; ETH-Zurich in Switzerland; and Sussex University and Nottingham University in the United Kingdom. The Paton Institute in the Ukraine has world-leading capabilities in E-beam deposition and is active in most phases of film deposition.

In Asia, the following organizations have active research programs: NEC, Riken Corporation, the University of Tokyo, Osaka University, and Nagoya University in Japan.

DATA SHEET 12.1. TECHNOLOGY FOR MULTI-LASER SURFACE MODIFICATION/COATING

Developing Critical Technology Parameter	Produces either a super-hard outer layer of the base material or a super-hard graded coating made up of the base material and an added constituent.
Critical Materials	Dependent on the coating to be deposited. The technique has had success with diamond, diamond-like carbon, and titanium carbide, among other sources.
Unique Test, Production, Inspection Equipment	Excimer, yttrium-aluminum garnet, and carbon-dioxide lasers. Other laser types might be substituted for these lasers.
Unique Software	Programs to control the multiplexing of the three lasers, the furnace temperature, and the gas mixtures.
Technical Issues	The interaction of the three lasers with the furnace temperature and the introduction of gas mixtures.
Major Commercial Applications	Wide application in materials requiring an extremely hard surface layer. Preliminary results on steel punches, golf club heads, and fuel-injector nozzles.
Affordability	Not an affordability issue.

RATIONALE

Surface modification/coating offers extremely hard coatings for a wide range of applications and does so with only surface heating. At the present time, the patented procedure can deposit diamond, diamond-like carbon, and titanium carbide films. Most of the applications with direct military application are primarily in the research or development stage. This includes wear/corrosion coatings for IR sensors (weapon systems), nose cones and domes, fibers for the manufacture of improved composite materials, and optical fibers for improved telecommunications. Improved tribological characteristics, coupled with improved wear, could significantly improve such items as bearings and raceways, and engine parts.

WORLDWIDE TECHNOLOGY ASSESSMENT

United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

At the present time, the only company known to be developing and using this technique is QQC in Dearborn, Michigan, although researchers at Penn State University have expressed an interest in the technique.

DATA SHEET 12.1. TECHNOLOGY FOR CUBIC BORON NITRIDE COATINGS

Developing Critical Technology Parameter	Extremely hard, durable coatings, with a hardness of 5,000 knoop (second only to diamond), a thermal conductivity of 13 (W/cm)(K) and a heat resistance of 1,000 °C. "Knoop" hardness is a method of measuring a material's hardness by its resistance to indentation
Critical Materials	Boron and nitrogen compounds
Unique Test, Production, Inspection Equipment	CVD equipment, sputter equipment, PVD equipment for deposition, and IR spectroscopy to characterize films.
Unique Software	None identified.
Technical Issues	Difficulty in obtaining stress-free coatings and difficulty in depositing films at temperatures < 1,000 °C.
Major Commercial Applications	Wide application in materials requiring surface protection from erosion. Also, should have wide application in the production of superior cutting tools, dies, and molds.
Affordability	Not an affordability issue.

RATIONALE

Cubic boron nitride (c-BN) is of great interest for several applications. It possesses great hardness and rigidity, optical transparency over a large wavelength range, chemical resistance (does not react with iron-based metals as do diamond films), and high thermal conductivity.

It should find wide military application in the manufacturing of military hardware and in military applications. In the manufacturing of military hardware, c-BN coatings could allow for faster machining or iron-based metals and for increased life to dies and molds. In military applications, c-BN coatings may improve the hardness, tribological requirements of such items as bearings and raceways, moving parts in conventional and jet engines, and super-hard films for optical elements.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●	Germany	●●●	Italy	●	Japan	●●●
Netherlands	●●	Sweden	●	UK	●	United States	●●●

Legend:	Extensive R&D	●●●●	Significant R&D	●●●	Moderate R&D	●●	Limited R&D	●

The demand for super-hard coatings is growing rapidly worldwide, and research includes not only diamond and diamond-like carbon coatings, but also c-BN. The principal countries with active programs in c-BN coatings are the United States, Germany, Japan, Italy, Sweden, and the, the United Kingdom.

In the United States, organizations with active programs include NASA, Caltech, Northwestern University, Oklahoma State University, Surmet Corporation, General Motors Research Laboratories, and Kennametal.

In Europe, the following organizations are pursuing research in c-BN films: the Fraunhofer Institute of Surface Engineering and Thin Films, the Technical University of Chemnitz-Zwickau, and Guenther and Co. GmbH in Germany; Philips BV and Hauzer Technology Coating Europe BV in the Netherlands; the Institute des Materiaux de Perpignan in France; the European Commission, Joint Research Centre in Italy; the University of Linköping in Sweden; and Hull University and York University in the United Kingdom.

In Asia, the following organizations are active: the University of Tokyo, Kyoto University, Osaka University, the Nippon Institute of Technology, and NIRIM in Japan.

12.2—BEARINGS

Highlights

- Development of magnetic bearings using high-temperature superconductors will result in
  - Improved compressors for space cryocoolers
  - Frictionless bearings for use in high-speed machining
  - Magnetic bearings for use in electric vehicles and magnetic guns.

OVERVIEW

Bearings are not only key elements in military equipment that use rotating elements, but they are essential for the operation of precision machine tools and metrology equipment used to manufacture military equipment. For many years, steel roller and tapered bearings were used almost exclusively in advanced military hardware and precision machine tools. In recent years, considerable effort has been expended in developing self-lubricating ceramic bearings. These bearings have longer life, less friction, and lower density than similar steel bearings.

More recent effort has been focused on aerostatic and hydrostatic bearings. These bearings use air and liquid to maintain a separation between the surfaces during their sliding or rotating motion. Their potential in high-/low-speed, high-precision equipment is unquestioned. They also operate quietly, thus offering the possibility of improved quiet propellers. Aerostatic and hydrostatic bearings approaches possess the following advantages:

- No wear of either surface
- High precision
- Operation at both very low and very high speeds
- High stiffness (hydrostatic bearings only).

Research on high-temperature superconductor, magnetic bearings is still in an early stage. Much of this program's success is related to continued research on high-temperature superconductors. Several potential applications have been discussed. The use of these bearings in space cryocoolers would avoid the problem of heat generation that occurs with the present gas bearings. Other possible applications include the support for the shaft of high-speed motors, the levitation force for high-speed locomotives, and energy storage. The concept of energy storage involves using the bearings with flywheels, where the flywheels rotate at very high speeds. The flywheel concept holds great promise for both off-peak energy storage of power plants and use a power source for vehicles, whether civil or military. A major problem has been related to concerns of flywheel breakage and the requirements to surround the system with heavy production shrouds. Another possibility is application in high-energy weapons.

RATIONALE

Magnetic bearings, manufactured from high-temperature superconductors, hold promise for a wide range of energy storage devices, particularly flywheel assemblies. Potential military applications include electrically powered vehicles, superior cryocoolers, improved motor operation (machine tools, power generators, and so forth), and magnetic guns.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.0-1)

Research in the area of superconducting bearings is widespread. The United States, Germany, Japan, France, and Switzerland are the world leaders. the Netherlands, the United Kingdom, Russia, Italy, and Finland also have active research programs.

LIST OF TECHNOLOGY DATA SHEETS
12.2 BEARINGS

DATA SHEET 12.2. TECHNOLOGY FOR SUPERCONDUCTING MAGNETIC BEARINGS

Developing Critical Technology Parameter	Offer promise for the mounting frame of flywheel energy storage systems (with application in electric vehicles and electric utilities) and spacecraft gyroscopes.
Critical Materials	High critical temperature superconductive material.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	CAD programs for design of structure.
Technical Issues	Major concerns are (1) developing superconducting material operating at higher temperatures and (2) problems with the breakage of the flywheel (used in energy storage) at very high rpm and the weight of the shroud necessary for protection.
Major Commercial Applications	Electric automobiles, electric utility companies, superior coolers, and the superconductive magnetic levitated (MAGLEV) railway systems.
Affordability	Not an affordability issue.

RATIONALE

Superconducting magnetic bearings are directly dependent on the advances in the development of superconducting materials. Materials have been developed with transition temperatures (T_c) in the 135 K range, considerably higher than the temperature of liquid nitrogen (77 K). Research on superconducting bearings is proceeding at a rapid pace throughout the world. The continued development of these bearings opens up a wide range of military applications, as well as civil applications that would directly affect the cost of military hardware.

Military applications should include magnetic guns, superior gyroscopes, high-power lasers, improved cryogenic coolers for space optics and guidance systems, and electric vehicles. In the world of civil applications, superconductivity (and the magnetic bearings using that technology) promises to revolutionize electric power systems throughout the world. Such a system would incorporate magnetic energy storage (using magnetic bearings), superconducting generators and motors (using magnetic bearings), and superconducting cable. Such advances in technology could play an important part in reducing the cost of electrical power and, thus, become an affordability issue.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Finland	●	Germany	●●●	Italy	●
Japan	●●●	Netherlands	●	Russia	●●	Switzerland	●
UK	●●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D (

Research in superconducting magnetic bearings is widespread throughout the world because these bearings are necessary items for the development of a new concept in electric power, whether it be for the electric power generation of a city or the power source of commercial vehicles. At present, the United States, Germany, and Japan, are considered the world leaders in the technology of superconducting magnetic bearings. However, several other countries have very advanced programs.

In the United States, the following organizations have programs in superconducting magnetic bearings: NASA, Argonne National Laboratories, the Jet Propulsion Laboratory (JPL), Stanford University, the University of Houston, the University of Texas, the University of Virginia, the University of Michigan, Cornell University, Georgia Tech, VPI, Texas A&M University, Boeing Defense and Space Group, MAGsoft, B&C Engineering, and Allison Engine Company.

In Europe, the following organizations have programs in superconducting magnetic bearings: CNRS, the Centre de Reserche et d'Etudes Avancees, the Society of Mechanics and Magnetics, the University of Savoy, and the Ecole Superior in France; the University of the Federal Armed Services, the Institute for Solid State Physics, the Forschungszentrum Karlsruhe, the IFW-Dresden, the University of Kassel, the University of Kaiserslautern, the Technical University of Chemnitz, and Höchst in Germany; the Moscow State Aviation Institute, the Research Institute of Nizhni Novgorod, and the Institute of Mechanics in Russia; Rutherford Applied Laboratory and Cambridge University in the United Kingdom; Helsinki University in Finland; the University of Bologna and the Polytechnical University of Torino in Italy; Delft University of Technology in the Netherlands; and ETH-Zurich in Switzerland. The European Space Agency (ESA) supports considerable work in this area.

In Asia, the following organizations have programs in superconducting magnetic bearings: NEDO, ISTEC, Kanazawa University, Chiba University, the University of Tokyo, and the Central Japan Railway Company in Japan.

12.3—METROLOGY

Highlights

- As critical dimensions of hardware become smaller, the positioning of the machining tool and the ability to measure that position become more important.
- The accuracy to which gears can be machined has a direct bearing on the noise and heat generated by the gears. Efforts to extend the metrology capability of gears to the 100-nm range should result in quieter and more efficient gear trains.
- The ability to operate high-quality coordinate measuring machines (CMMs) in the shop environment would result in a cost saving because the necessity of taking the part to a centrally located measuring room for high-precision dimensional measurements is very time consuming.

OVERVIEW

Metrology, in some form, has been used since the beginning of civilization. It took on additional importance during the Industrial Revolution when parts were no longer manufactured as one-of-a-kind. During the intervening years, metrology has advanced from measuring angles and lengths in inches and degrees to measurements in fractions of microns and arc-seconds. Modern metrology equipment includes gauge blocks, surface profilers, angular measuring equipment, laser-based measuring systems, coordinate measuring machines, and so forth.

Present developing technology can be separated into two parts: increased measurement capability and the use of advanced equipment in the shop working area (as opposed to operation only in controlled environments). This subsection addresses two technologies in the first part and one in the second. The following programs to increase measurement capability are listed: (1) to produce gear-measuring equipment that is not only faster than conventional equipment but will have measurement accuracies less than 1 µm and (2) to improve the capability of more accurately measuring the position of the spindle of a machine tool. Work is also being carried out to produce high-quality coordinate measuring machines that can withstand the environment of the shop floor and, thus, carry out inspections next to the production machines.

RATIONALE

Accurate dimensional inspection (metrology) is essential for designing, developing, manufacturing, and using most military and commercial hardware. In addition, meaningful interchangeability of parts requires that dimensional accuracy be maintained when replacement parts are manufactured. Until recently, it was satisfactory if these instruments had resolutions and/or accuracies in the 0.5- to 1.0-µm range. However, demands for ever-decreasing dimensions in products—whether for use in micromachines, MEMS, or semiconductor devices—have placed increasing demands on the metrology discipline. Considerable effort is being expended in what is sometimes called “micro-metrology.” Linear measurements in the sub-100-nm range will assume greater importance as the capability of lithography is extended to that range.

Improvements in metrology should result not only in more reliable military hardware, but also in reduced costs. A universal agreement concerning the best techniques could make cost reductions significant.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.3-1)

Metrology is a critical technology in any industrialized country, and, as a result, most such countries have ongoing programs to improve metrology. The United States, Germany, and Japan appear to have the most extensive programs. However, Denmark, France, Italy, and the United Kingdom have substantial efforts, with Australia, the Netherlands, and Sweden having niche efforts.

Country	Machine Tool Metrology	Gear Metrology	Factory Floor CMMs
Austria			●
Denmark	●●	●●	
France	●●	●●	●●
Germany	●	●●	●●●
Italy	●●		
Japan	●●●●		●●●
Netherlands		●	
Sweden			●
Switzerland	●●		●
Taiwan	●		
UK	●●	●●	●
United States	●●●	●●●	●●●

Legend:

Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.3-1. Advanced Fabrication and Processing WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
SECTION 12.3. METROLOGY

DATA SHEET 12.3. MACHINE TOOL METROLOGY

Developing Critical Technology Parameter	There are no quantitative parameters for this technology. Studies are being conducted on techniques to measure the position of the spindle more accurately. Techniques include laser triangulation and IR technology. Time frame: 5–10 years.
Critical Materials	Sensors to measure displacement, velocity, acceleration and deceleration, force and strain, pressure, or temperature.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Technical Issues	The sensors used in the system. The ability to measure the spindle position more accurately than present capabilities permit and to reflect that measurement into a feedback to position the spindle more accurately (self-correction).
Major Commercial Applications	Broad application in most machining operations used in the manufacture of commercial hardware.
Affordability	Increased metrology capability and reduced time for measurements reduces overall costs for gears.

RATIONALE

Improvements in the measurement (and control) of the spindle position will result in improvements in overall machine tool positioning accuracy. Such accuracy is critical in the machining of certain military hardware. Thermal effects alone can affect the positioning accuracy by 2 μm. As the positioning accuracy of machine tools is improved by other methods (e.g., better raceways, bearings, and so forth), the technique to determine the actual position of the spindle must improve similarly. This would be of greatest importance in grinders and diamond turning machines used to finish hardware with the most stringent accuracy requirements (e.g., certain optical elements, hemishells for nuclear weapons, and so forth).

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●	Japan	●●●●	Netherlands	●
Switzerland	●●	Taiwan	●	UK	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Although the available literature on research in this technology area is sparse, the intense worldwide competitiveness in machine tool sales make it safe to assume that most major machine tool manufacturers have programs. Available literature indicates that the United States and Japan have the most far-reaching programs. It is assumed that Germany and Switzerland also are active.

In the United States, the following organizations have programs: Oak Ridge Center for Manufacturing Technology, Sandia National Laboratories, Michigan Technological University, the University of Washington, and Boeing Commercial Airplane Corporation.

In Europe, the following organizations have programs: Messtechnik GmbH in Germany; Sipp and Dixi in Switzerland; LGP ENIT and Analogy in France; Delft University of Technology in the Netherlands; and Birmingham University, Nottingham University, and Trent University in the United Kingdom.

In Asia, the following organizations have programs: Mitsubishi, NTN, Hitachi, Seiko, Toyo Engineering, Nagoya University, and Kobe University in Japan and the National Taiwan University and the National Huwei Institute of Technology in Taiwan.

DATA SHEET 12.3. GEAR METROLOGY

Developing Critical Technology Parameter	Measure gear parameters 10^2 to 10^3 times faster than CMMs (3 to 4 gears per second), with submicrometer accuracies.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Technical Issues	Measurement technique, analytical programs, and so forth.
Major Commercial Applications	Application in the manufacture of a range of gears that require very accurate tolerances (e.g., helicopter gear sets and jet engines).
Affordability	Increased metrology capability and reduced time for measurements reduces overall costs for gears.

RATIONALE

Improved metrology of gears should result in gears that can meet more stringent specifications. This should result in quieter gears for naval vehicles and gears with increased power density for use in helicopters and other military hardware.

In addition, the more accurate and faster measurement of the gears and the resultant improvement in gear quality should improve the reliability and life of gears, and reduce the cost of inspection, maintenance, and replacement.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany ●● UK ●● United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in improved metrology of gears is somewhat limited, with the main effort apparently existing in the United States, Germany, and the United Kingdom.

In the United States, the following organizations appear to be the major research institutions: NIST, Penn State National Center for Advanced Gear Manufacturing, Oak Ridge Metrology Center, Ohio State University, Illinois Institute of Technology, Mahar Corporation, M&M Precision Systems Corporation, General Motors Corporation, Bell Helicopter, Caterpillar, and Fellows.

In Europe, the following organizations have research programs: the Technical University of Munich, Leitz, and Frenco in Germany and the UK Gear Technology Centre, Stewart Hughes, and the University of Newcastle Upon Tyne and Huddersfield University in the United Kingdom.

DATA SHEET 12.3. FACTORY-FLOOR-CAPABLE COORDINATE MEASURING MACHINES (CMMs)

Developing Critical Technology Parameter	The design and manufacture of CMMs so that the critical operating parts are not affected by the shop environment. The goal is to produce CMMs with accuracies in the 3.5 µm = L/200, where L is the linear distance being measured, in a temperature from 10 to 35 °C. Time frame: 5–10 years.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithm to analyze input from sensors.
Technical Issues	Techniques of sealing the critical moving parts of the machine from the shop environment without negatively affecting the machine accuracy. A question also arises concerning the best temperature at which to measure the part (e.g., room temperature, application temperature, and so forth).
Major Commercial Applications	Broad application in most machining operations used in the manufacture of commercial hardware.
Affordability	Having the CMMs on the shop floor, near the machining centers, would result in reduced costs of performing product inspections.

RATIONALE

The necessity of taking the part to a centrally located measuring room for high-precision dimensional measurements is very time consuming. Having high-quality CMMs operating in the shop-floor environment would facilitate the inspection of product, both during and after machining. This would reduce the time (cost) to perform quality checks of product.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany ● UK ● United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in this technology is somewhat limited.

In the United States, Brown and Sharp, LK Metrology, Inc., SMX Corporation, Cordax, Giddings and Lewis-Sheafield, and Romer, Inc., have developed products.

In Europe, Zeiss in Germany has a product, and Aberlink in the United Kingdom has development programs.

12.4—NON-DESTRUCTIVE INSPECTION AND EVALUATION

Highlights

- The use of shearographic techniques should increase the technical capabilities for the detection of flaws.
- Smart materials could revolutionize the inspection and evaluation of hardware by incorporating within the hardware sensors that could detect flaws.
- The application of data fusion technology to NDE should reduce the time/cost to perform more advanced analyses.

OVERVIEW

NDE encompasses a wide range of disciplines, including eddy current, magnetic testing, penetrant testing, radiographic testing, and ultrasonic testing. Each of these techniques is used in several different applications; however, they all have one thing in common: They are used for the detection of defects after an item or structure has been manufactured and requires periodic inspection. All these techniques have been used for quite a few years, and only minor changes have been incorporated into the procedures. Most changes have resulted from improvements in detection equipment. In this subsection, we describe three new NDE techniques: digital shearography, the use of smart materials, and data fusion.

Shearography is more traditional. It is a technique that is used to analyze finished product. In its simpler sense, shearography is an existing technology; however, it has several drawbacks. Digital shearography is an approach aimed at improving the technique. In short, shearography is a nonscanning, laser-based interferometry system used to detect areas of stress concentration caused by anomalies in materials. Digital shearography combines these techniques with charged-coupled device (CCD) cameras and computers to improve the image and allow analyses of the results. Digital shearography can examine substances as large as 1 ft square and is portable so inspection need not to be place in a laboratory.

Shearography has a major advantage over conventional non-destructive test (NDT) techniques (e.g., dye penetrant, magnetic particles, and radiography) used to detect flaws. The conventional techniques detect all visible flaws, but shearography, by examining not the flaws but the flaw-induced strain, provides more information on the criticality of the flaw. Potential military applications include the detection of subsurface flaws in aircraft panels and the detection of voids in composite materials.

The use of smart materials is a more radical approach because the sensors used to detect flaws in the structure are built into the structure and can be used to monitor quality/reliability either during manufacture or after the product is completed. The concept of smart materials is also an emerging technology in materials technology. In that application, the sensors detect some “designed-for” parameter and respond with a counteraction (e.g., damping engine vibrations, silencing refrigerators and aircraft cabin noise, and so forth).

Smart materials include technologies such as piezoelectric materials, shape memory alloys, and magneto-strictive fluids. The field of piezoelectric materials is the most advanced, and some commercial applications have been developed. However, widespread use of these technologies is still in the future. Potential civil and military applications abound, with civil applications including sensor determination of aging in building, bridges, and so forth; determination of maintenance requirements for engines, aircraft, and so forth; and chromogenic applications (e.g., self-dimming rear-view mirrors, architectural windows, and so forth). Potential military applications include smart skins for improved submarine signature control (cancel incoming acoustic radiation), improved helicopter rotor-blade trailing edge flaps, and aircraft wings that can change shape to minimize drag.

Data fusion is a technique that uses data from a group of NDE sensors rather than using data from a single sensor. It has potential application in a wide range of disciplines. In essence, data fusion is a technique in which data from multiple—and perhaps diverse—sensors are correlated into digitally formatted products. These products provide a user with complex information in a user-friendly format so that decisions can be made quickly and accurately.

RATIONALE

The optimal use of structural materials, as well as the introduction of high-performance systems for military applications, is dependent on the ability to detect and characterize strength-limiting flaws and defects. As military systems become more complex and, at the same time, military budgets decline, existing NDE techniques must be refined and new, more sensitive and less expensive techniques must be developed.

The technologies addressed in this section meet both of these requirements. They result not only in increased technical capabilities of the final product, but also in cost savings.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.4-1)

Countries with aerospace industries have shown a particular interest in digital shearography because of its potential in detecting flaws in the composite structures commonly used in aircraft structures. (To date, shearography has not detected disbonds in some composite materials.) The United States, France, Germany, and the United Kingdom appear to be the leading countries in shearography development. China, Italy, Portugal, Singapore, and Switzerland have lesser programs, although ETH-Zurich is a world-class facility.

Research in smart materials is one of the most intense research efforts worldwide. The United States, France, Germany, Japan, and the United Kingdom are the world leaders. Austria, China, Italy, and the Netherlands are also pursuing research in this area.

Country	Shearography	NDE with Smart Materials	NDE Data Fusion
Austria		●	
Belgium			●
Denmark			●
France	●●	●●●●	●●●
Germany	●●	●●●●	●●
Hong Kong (PRC)	●		
Italy	●●●	●	
Japan		●●●●	●●
Korea		●	
Netherlands	●	●	●●
Singapore	●		
Switzerland	●		●
UK	●●	●●●	●●●
United States	●●●●	●●●●	●●●●

Legend:
Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.4-1. Non-destructive Inspection and Evaluation WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
SECTION 12.4. NON-DESTRUCTIVE INSPECTION AND EVALUATION

DATA SHEET 12.4. DIGITAL SHEAROGRAPHY

Developing Critical Technology Parameter	Provides a large-area, quantitative analysis of stress concentrations resulting from either the vibration of a structure or existing in composite materials in aging aircraft. Inspection speed of an order of magnitude higher than conventional ultrasonic techniques. Time frame: 5–10 years.
Critical Materials	Lasers, CCD cameras, and so forth.
Unique Test, Production, Inspection Equipment	Laser system, CCD camera, and image processor.
Unique Software	Software algorithm to process information.
Technical Issues	None identified.
Major Commercial Applications	Useful in a wide range of commercial hardware, particularly aging aircraft.
Affordability	Improved shearography would result in reduced costs for performing some NDI tests.

RATIONALE

Shearography can provide a faster, more superior analysis of subsurface flaws in many subjects, including aging aircraft. It is a portable, nonscanning technique and can analyze up to a square foot of surface at one time. It should be useful in a wide range of military hardware, including aging aircraft and hardware that is susceptible to vibration (e.g., launch vehicles, missiles, and so forth). Its development will improve the safety of older aircraft and reduce maintenance costs.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●	Germany	●●	Hong Kong (PRC)	●	Italy	●●●
Korea	●	Netherlands	●	Singapore	●	Switzerland	●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

A wide range of countries are active in the digital shearography, with the United States and Europe appearing to have the most research.

In the United States, the following organizations have research programs: WPAFB, NASA/Langley, Penn State University, Michigan State University, the University of New Mexico, Oakland University, Ford Motor Company, and Boeing Defense and Space Group.

In Europe, the following organizations have research programs: CISE in Italy; Aerospatiale and SEP in France; the University of Kassel and Dr. Ettemeyer GmbH and Co. in Germany; the University of Surrey, the University of Warwick, and John Moores University in the United Kingdom; Delft University of Technology in the Netherlands; and ETH-Zurich in Switzerland.

In Asia, the following organizations have research programs: the City University in Hong Kong (China); the Jun-Bok University in Korea; and the National University of Singapore in Singapore.

DATA SHEET 12.4. NDE USING SMART MATERIALS

Developing Critical Technology Parameter	Theoretically, can sense (and often take corrective action) of a wide range of developing problems (e.g., local stress, corrosion, fatigue, vibration, noise, and so forth).
Critical Materials	Piezoelectric materials, shape memory alloys, magnetostrictive fluids, fiber optic material, and thermoplastics. Many of these are incorporated into MEMS structures.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithms to process information.
Technical Issues	The complexity of integrating the signal from the sensor to the control circuitry.
Major Commercial Applications	Useful for the NDE of a wide range of commercial hardware, including items such as launch vehicles, aircraft, heavy equipment, trains, and so forth.
Affordability	This technology should not only reduce the amount of rejected hardware but also improve the long-term reliability of military equipment. The reduction of rejected hardware, the reduction of built-in latent failures, and the capability of detecting operationally induced failure mechanisms should lead to an overall reduction of costs.

RATIONALE

These materials can sense a wide range of potential problems in critical hardware. They pose the possibility of detecting problems not only in the manufacturing process, but also of detecting defects either built into the end item or defects that might develop during service. The detection of problems during manufacture could lead to the optimization of the manufacturing process and the subsequent reduction of rejected products. This would be an affordability issue, resulting in reduced costs. The early detection of defects will also reduce the number of latent failure mechanisms that might be built into the hardware, thus improving the long-term reliability.

The detection of defects that arise in the hardware during operation (allowing the opportunity for corrective action) could reduce catastrophic failure of hardware that could impact not only personal safety, but expensive damage or destruction of the equipment.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	France	●●●●	Germany	●●●●	Italy	●
Japan	●●●	Korea	●	Netherlands	●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

The number of facilities engaged in smart materials is too extensive to list in its entirety. The following is a representative sampling of the facilities.

- ***United States***
  - Army Research Laboratory (ARL)
  - DOE
  - NRL
  - Naval Sea Systems Command/Crane
  - Langley Research Center

    - WPAFB
    - ORNL
    - Sandia National Laboratories
    - JPL
    - Illinois Institute of Technology
    - Virginia Tech
    - University of Maryland
    - A. James Clark School of Engineering
    - University of Buffalo
- University of Kentucky
- Iowa State University
- Johns Hopkins University
- University of Illinois
    - Honeywell
    - Lockheed Martin
    - Northrup Grumman
- McDonnell-Douglas
- Westinghouse.

- ***France***
    - Institut National des Sciences Appliques de Lyon
    - Bertin
    - St. Cyr l'Ecole
    - Ecol Central de Lyon
    - Institute de Productique
    - Alcatel
    - CNES
    - MATRA Marconi
    - Cedrat Recerche.

- ***Germany***
    - University of Stuttgart
    - University of Hamburg
    - University of Bochum
    - Forschungszentrum Karlsruhe GmbH
    - Schott Glass
    - DLR
    - Dornier Satelliten Systems GmbH.

- ***United Kingdom***
    - DERA (The UK Ministry of Defense)
    - University of Hull
    - Cranfield University
    - University of Sheffield
    - University of Bristol
    - Oxford University.

- ***Austria***
  - University of Vienna.
- ***Italy***
  - Italian Aerospace Research Center.
- ***The Netherlands***
  - Katholieke Universiteit of Leuven.
- ***Japan***
  - Science University of Tokyo
  - Tohuko University
  - Chiba University
  - University of Tokyo
  - Kyoto University
  - Kobe University
  - Aichi Institute of Technology
  - National Research Institute for Metals
  - Yasui Laboratories
  - MITI Frontier Program.
- ***Korea***
  - Postech Pohang.

DATA SHEET 12.4. NDE DATA FUSION

Developing Critical Technology Parameter	Improves NDE data collection and assessment by using the input from multisensors (rather than from a single sensor). Processing data and providing an integrated analysis of the item under test.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	Software algorithms to process information from multisensors.
Technical Issues	Techniques to embed sensors, type of sensors used, and technique to protect sensors used on equipment operating in hostile environments.
Major Commercial Applications	Machine tool monitoring, aircraft, automotive, and medical applications.
Affordability	Improved NDE data fusion could reduce the overall costs by reducing waste and improving reliability.

RATIONALE

Data fusion, *per se*, has potential application in a wide range of disciplines. In essence, data fusion is a technique in which data from multiple, and perhaps diverse, sensors are correlated into digitally formatted products. These products provide a user with complex information in a user-friendly format, so that decisions can be made quickly and accurately.

Many applications involve rather similar techniques. In machine tools, it might involve the placement of multiple sensors on a machine spindle or within the mass of the machine tool. This would facilitate monitoring spindle placement, temperature, and so forth or overall machine tool condition. In aircraft and automotive, data fusion might involve placing sensors to monitor the condition of the aircraft or automobile (internal temperatures, exhaust, emissions, and so forth). Satellite observation, whether oceanographic, earth resources, or intelligence gathering, is another area of growing interest. Battlefield data collection is a military-unique application in which the collected data could provide timely inputs for command decisions. Mobile robots are another fertile field of research for data fusion. For mobile robots, data fusion includes not only multisensor fusion and control of a single robot, but also cooperative interactions among multiple roots.

WORLDWIDE TECHNOLOGY ASSESSMENT

Belgium	●	Denmark	●	France	●●●	Germany	●●
Japan	●●●	Netherlands	●●	Switzerland	●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Data fusion research is being carried out throughout the industrialized world. At present, the United States, France, and Germany appear to be the leaders.

In the United States, the following organizations have active research programs: ARL, NRL, NASA, NIST, Battelle Memorial Institute, LLNL, JPL, and Sandia National Laboratories, the University of Texas, the University of Kentucky, Stanford University, Yale University, the University of Southern California, the University of Illinois, Carnegie Mellon University, MIT, IBM, General Motors Corporation, Boeing Aerospace, United Technologies Research Center, Hughes Research laboratories, Metron, Inc., and PSR.

In Europe, the following organizations have active research programs: the University of Paris-Sud, Mistral Consortium, EDF-Chatou, Dassault Aviation, INSA de Rennes, ILOG, LIFIA-IMAG, CNRS, Alcatel-Alsthom Research, and Thomson-CSF in France; the University of Reading, CNR, TWI, British Aerospace, and Ellis Harwood, Ltd., in the United Kingdom; FGAN, Humboldt University, Technical University of Braunschweig, and the University of Erlangen in Germany; the National Aerospace Laboratory, Hollandse Signaal, and TNO-FEL in the Netherlands; the Katholieke Universiteit of Leuven in the Netherlands; Aalborg University in Denmark; and the University of Zurich and the Swiss Federal Institute of Technology in Switzerland.

In Asia, the following organizations in Japan have programs in data fusion: Kobe University, Keio University, Nagoya University, Mitsubishi Materials Research, and Hitachi Machine Tool Company.

12.5—PRODUCTION EQUIPMENT

Highlights

- The development of spindles capable of operating at higher speeds and power would reduce the cost of machining.
- Improved grinding machines would result in more powerful jet and diesel engines and more accurate guidance systems.
- The continued development of parallel kinematic machine tools may result in improved machining capabilities and reduced cost of the machining operation.
- The use of MEMS technologies to improve military hardware and to reduce costs may be one of the most significant advances in developing superior and less expensive military hardware.
- Improved monitoring of machines and tools should reduce the cost of military hardware.

OVERVIEW

This subsection addresses various developing production technologies that either will provide superior final product (military and/or commercial product) or will reduce the costs of manufacturing existing product. Included in the subsection are several technological advances that may improve the final product and several modifications that may result in decreased costs. The former includes the following technologies:

- Improved grinding machines that could result in product manufactured to closer tolerance
- Machine tools based on the parallel kinematic concept (e.g., Stewart platform or hexapod)
- Extremely small machine tools (micromachines) that can be used to manufacture miniature hardware
- MEMS, a revolutionary technology or manufacturing miniature hardware that combines both electronic and mechanical on a monolithic substrate.

The Stewart platform is the basis of the hexapod milling machine design. The design also has application in flight simulators, telescope mounts, and space-borne laser reflectors. In the machine tool arena, particular attention is being given to its development as a tool for manufacturing nanometer-size items (nanotechnology).

Hexapods are based on the Stewart platform. Companies in numerous countries are investigating the use of hexapods as machine tools. Indeed, initial designs have been manufactured and are in the process of being evaluated. While some limited use has been found for the equipment, sufficient problems still limit their use at the present time. The main problem is that the positioning accuracies are on the order of five times worse than that of the best milling machines (although comparable to many existing machines). Such equipment might find a niche in the manufacture of micro- or nano-scale products.

Tetrahedral tripods are a third class of parallel kinematic machines. Efforts are still in the research stage, but such equipment may avoid some of the problems inherent in Stewart-platform-based equipment.

Micromachines are being pursued primarily in Japan, coordinated by the Micromachines Center and supported by MITI. The goals of this program are to manufacture minute items, such as invasive medical micromachines and maintenance systems for power plants. The technology, although different from MEMs, has the same general goals as the MEMS concept.

MEMS uses the techniques developed for the manufacture of integrated circuits to fabricate devices that incorporate, on a semiconductor substrate, not only integrated circuits, but also mechanical structures that can be used for a range of applications. MEMS technology includes three important characteristics: miniaturization, multiplicity, and microelectronics. By using semiconductor device manufacturing technology, these packaged

MEMS-based systems are very small (ranging from 1 mm to 2 cm in size), can be manufactured in quantity using conventional pholithographic techniques, and incorporate complex electronic circuitry.

Until the advent of MEMS, miniaturization was a concept most often associated with electronics. The continual miniaturization of electronic systems has been one of the pillars of the advanced technologies used in military and civil hardware. The decrease in size, coupled with the increase in processing power, of computers is a prime example of the advances in electronic technology. In MEMS technology, actuators, sensors, and medical devices incorporating mechanical structures (e.g., levers, springs, motion sensors, and so forth) and integrated circuits are manufactured on semiconductor substrates, thus using the miniaturization capabilities of integrated circuit technology. The use of semiconductor manufacturing technology also results in the batch processing inherent in photolithographic-based semiconductor processing and makes it possible to fabricate thousands of components as easily as a single component. As a result, the cost of the components is reduced significantly, thus extending the use of the products to a wider range of applications. The incorporation of these mechanical structures either into microcircuit chips or on associated substrates (hybrid device) provides the intelligence to the devices that allow their use without the cumbersome external components that were often required to interconnect discrete components.

Technologies that may result in decreased costs include:

- Tool monitoring and sensing, which may result in more cost effective technique for determining tool life
- Machine degradation monitoring, which may result in a more cost-effective technique for determining machine tool maintenance
- High-speed spindles, which will decrease the time required to machine many parts, thus reducing the final cost
- First-part-correct programs, which would reduce the cost of having to make two or three items before the design/manufacturing process was corrected to produce a product that met design specifications.

RATIONALE

Numerically controlled (NC) machine tools find wide application in the defense and aerospace industries. Their ability to produce complex shapes with minimum setup time and fixturing makes them critical to the batch processing of components for modern weapons systems. While it is difficult to determine the results of developing technologies (some may never reach fruition), any manufacturing technologies that improve the characteristics of military hardware and/or reduce the cost of that hardware are of significant military importance. For example, improved grinding machines could result in more powerful and efficient jet engines and more accurate guidance systems. While the future of hexapods and micromachines is not clear, significant effort is being expended in these technologies. The use of improved hexapods may result in superior product and/or less expensive product or it may find use in complex parts. The significant interest in the use of the Stewart platform as the “motion system” for sensitive telescopes should also be noted. Micromachines (primarily pursued by Japan) is envisioned as a technology that may find use in miniature medical and industrial products. Success in these applications would certainly lead to applications in military hardware. MEMS, while included here as a developing technology, is, at the same time, a technology that has found present applications in several commercial applications (e.g., accelerometers for automobile airbag deployment). The future applications of this technology appear to be extensive, and few doubt that the military applications will be significant.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.5-1)

Several countries possess advanced machine tool technology, whether in grinders, milling machines, or turning machines, and all are pursuing continued improvements. Efforts to achieve high-speed spindles with large force and feed-rate capabilities, as well as the capability to monitor tool and machine tool condition, has been a continuing effort by many universities and machine tool companies. A large international consortium, IMS-SIMON, has been formed to address the problem of sensor monitoring of machine tools and cutting tools. The consortium includes companies from the United States, Canada, Germany, Italy, Japan, Spain, and Switzerland. Research in parallel kinematic machine tools is extensive in most of the countries with advanced machine tool industries. The United States, Germany, Japan, Sweden, and Switzerland appear to be the most involved.

Country	Manufacturing	Parallel Kinematic Machines	MEMS
Argentina	●●		
Brazil	●●		
Canada	●●		●●
Czech Republic	●●		
China	●●		
France	●●●		
Germany	●●●●	●●●	●●●
India	●		
Israel	●●		
Italy	●●●		
Japan	●●●●	●	●●●●
Netherlands			●
Norway		●	●
Romania	●	●	
Russia	●●	●	
Spain	●●●		
Sweden	●●	●	●
Switzerland	●●●●		
Taiwan	●●	●●●	
UK	●●	●	●●●
United States	●●●●	●●●	●●●●

Legend:
Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.5-1. Production Equipment WTA Summary

MEMS research is extensive throughout the industrialized world. While the United States, Germany, and Japan appear to have the most extensive programs, France, the Netherlands, Norway, Sweden and the United Kingdom also have advanced programs.

LIST OF TECHNOLOGY DATA SHEETS
SECTION 12.5. PRODUCTION EQUIPMENT

DATA SHEET 12.5. HIGH-SPEED, HIGH-POWER SPINDLES WITH HIGH-FEED RATE

Developing Critical Technology Parameter	The requirement is to obtain spindles that have not only high-speed capability, but can operate at that speed with both high force and feed rates. The overall goal is to develop spindles with the following capabilities: 100,000 rpm @ 100 kW and with a feed rate of 3,000 in. per minute.
Critical Materials	Bearings, motors, seals, cooling, and lubrication.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Software algorithms to handle high-speed machining/grinding.
Technical Issues	Bearings, acceleration, and deceleration of the tool, chip control, keeping the coolant material on the spindle, and having the controller capable of handling the high speed.
Major Commercial Applications	Large-scale manufacturing: aerospace, automotive.
Affordability	The use of higher speed spindles would allow the fabrication of many critical parts in much less time.

RATIONALE

The use of such spindles would fall into the category of "affordability." Their use would allow the fabrication of many critical parts in much less time. In addition, the high-speed spindles make lighter and faster cuts and minimize heat transfer to parts. This allows the machining of thinner products, without damage to the products, and would minimize the need for subsequent fabrication steps (e.g., finishing). Applications would include not only the hogging out of bulk materials, but the fabrication of critical dies and molds.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany	●●	Japan	●●	Switzerland	●●	United States	●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

In a period of high competition in manufacturing, research in high-speed spindles in being carried out in most countries that have advanced machine tool capabilities. The United States appears to be the major area of research, with Germany, Japan, and Switzerland having very capable programs.

In the United States, the following organizations have programs: NIST, the University of Florida, Purdue University, Georgia Tech, Milicron, Boeing, and the National Center for Manufacturing Science (NCMS).

In Europe, the following organizations are active in research: Datron-Electronic GmbH and the Fraunhofer Institute in Germany and IBAG and Step-Tek in Switzerland

In Asia, the following organizations are active in research: Shin Nippon Koki and Toyoda in Japan.

DATA SHEET 12.5. CUBIC BORON NITRIDE (cBN) GRINDING WHEELS FOR HARDENED STEEL GEARS AND BEARINGS

Developing Critical Technology Parameter	Important for grinding steel gears (diamond-coated wheels are of limited value in grinding hardened steel) to improve power density of gearbox.
Critical Materials	cBN.
Unique Test, Production, Inspection Equipment	None identified.
Unique Software	None identified.
Technical Issues	Preparation of the cBN, the adherence of the cBN to the wheel, and a grinding machine capable of handling cBN-coated wheels.
Major Commercial Applications	Helicopters, engines, and so forth.
Affordability	cBN-coated wheels will last much longer than conventional wheels.

RATIONALE

Grinding of steel gears is a critical step in the manufacture of helicopter gearboxes, quiet gears, and so forth. Properly ground gears possess improved power density and reliability and operate more quietly than conventionally ground gears. Diamond grinding wheels cannot be used to face steel gears because the iron reacts with the diamond and deteriorates the abrasive properties of the wheel.

WORLDWIDE TECHNOLOGY ASSESSMENT

Austria	●	Germany	●●	Ireland	●	Japan	●●
Korea	●	Switzerland	●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research and manufacture of cBN grinding wheels are widespread in the industrialized world.

In the United States, the following organizations have programs: the University of Connecticut, GE Superabrasives, Kapp Tech, Inc., Norton Co., General Motors Corporation, and Weinig, Inc.

In Europe, the following organizations have programs: IFW/University of Hannover, Lapport & Sohn, and Lach Diamant in Germany; WST Winterthur in Austria; the University of Dublin in Ireland; and Ewag AG in Switzerland.

In Asia, the following organizations have programs: the University of Tokyo and Toyoda in Japan and Korea Tungsten Co. in Korea.

DATA SHEET 12.5. PRECISION PROFILE GRINDERS

Developing Critical Technology Parameter	A work head run-out < 0.1 microns and a wheel surface speed > 100 m/second @ 50 kW grinding power help achieve 6-sigma quality for ground parts.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	None identified.
Technical Issues	The bearing and the wheel strength.
Major Commercial Applications	Large-scale manufacturing: aerospace, automotive.
Affordability	Not affordability issue.

RATIONALE

Such grinders would result in a product manufactured to much closer tolerances, finer fits, and so forth. This could be of significant value in the manufacture of jet engines and more accurate parts for guidance systems.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany	●●●●	Italy	●	Japan	●●●●	Switzerland	●●●●
UK	●	United States	●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

While most manufacturers of grinding equipment can be expected to continue efforts to improve their product, only one document was found indicating a specific effort to improve the specifications of their product significantly. NCMS, a consortium of U.S. companies, has listed a "precision production grinder" as one of their areas of interest.

Other U.S. organizations expected to have active programs in developing advanced grinders would include Bryant, CNC Systems, and Campbell.

European organizations expected to have active programs in developing advanced grinders include Junker, Overbeck, Schaudt, BWF, and Studer in Germany; Tripet, Kellenberger, Studer, Ewag AG, Voumard, and Doebeli in Switzerland; Tachella in Italy; and Jones and Shipman in the United Kingdom.

Asian organizations expected to have active programs in developing advanced grinders include Citizen, Koyo, Okuma, Toyoda, Shigiya, and Toyo in Japan.

DATA SHEET 12.5. PARALLEL KINEMATIC MACHINE TOOLS (STEWART PLATFORM, HEXAPOD, PARALLEL LINKAGE STRUCTURES, AND SO FORTH)

Developing Critical Technology Parameter	Parallel kinematic machine tools are a new concept in machine tool design. Existing developmental models have several drawbacks, and considerable research is being done to overcome these problems. If such machines can be improved to possess positioning accuracies of < 10 microns, velocity of 1 m/second, and spindle speeds in the 50,000-rpm range, they would find a definite niche among machine tools.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools.
Unique Software	Unique algorithms to control six axes (for the Stewart platform and hexapod) and three axes (for the tetrahedral tripod).
Technical Issues	Need to improve limitations in accuracy resulting from thermal distortions and to achieve a design that is less costly.
Major Commercial Applications	Applications would include machining of small, complex parts or for use in pick-and-place systems.
Affordability	Not an affordability issue.

RATIONALE

Proponents of the 6-degree of freedom Stewart platform (hexapod) approach believe that the machines built on this structure will introduce a degree of precision machining productivity and economy not possible with conventional machine tools. The combination of structural rigidity and stiffness, high-speed tool positioning, and full six-axis motion will find wide use in the automotive and aerospace industries. Figures 12.5-2 and 12.5-3 are pictures of a hexapod and a Stewart platform, respectively.

Proponents of the simpler tetrahedral tripods believe their approach will be superior because of its speed of motion, larger ratio of work volume to machine volume, lower inertia, and easier solution to the kinematics problems.

Both approaches of parallel kinematics machine tools are being pursued, and the end result should be a superior class of tools, albeit for unique applications, that should result in superior, and possibly less expensive, final products.

WORLDWIDE TECHNOLOGY ASSESSMENT

Germany	●●●●	Japan	●	Norway	●	Russia	●
Sweden	●	Switzerland	●●●●	UK	●	United States	●●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research on the Stewart platform (hexapod) approach concept in quite extensive. The following organizations are actively building and/or evaluating machines: NIST, Giddings and Lewis, Ingersoll Milling Company, and Hexal Tornado in the United States; Mikromat, ZFS/University of Stuttgart, University of Hannover, IFW, and Dyna-M in Germany; Geodetics, ETH-Zurich, and Demaurex Aria Delta in Switzerland; Multicraft in Norway; British Aerospace in the United Kingdom; Lapic in Russia; and Hexa in Japan.

JMC in Sweden is pursuing a tripod approach, and the University of Illinois in the United States is researching a tetrahedral tripod.

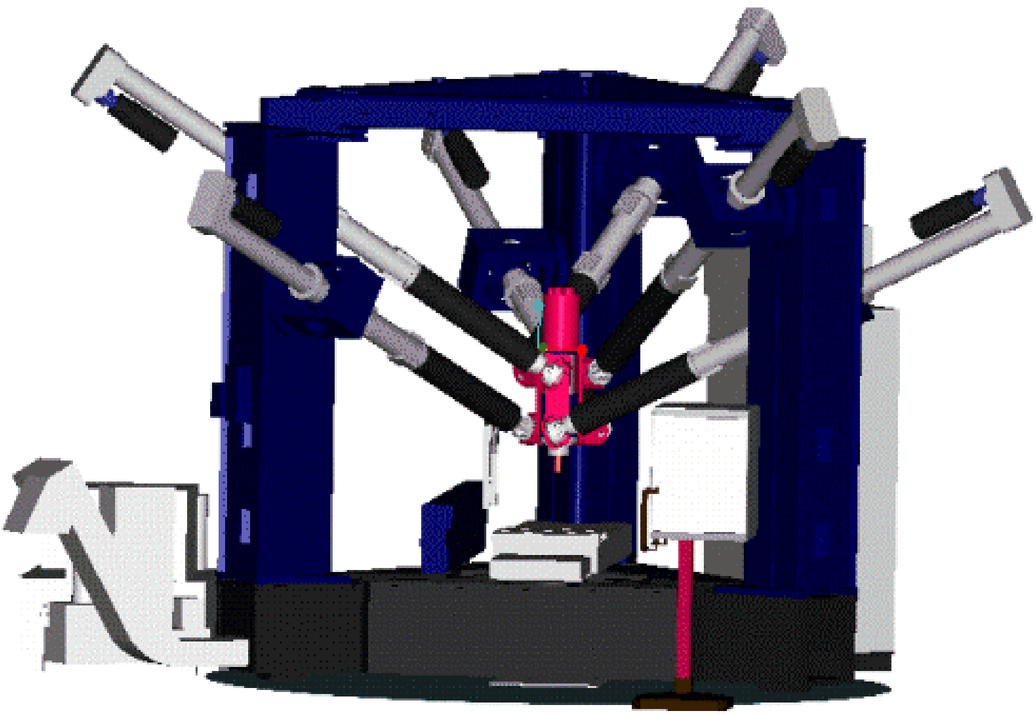


Figure 12.5-2. Hexapod

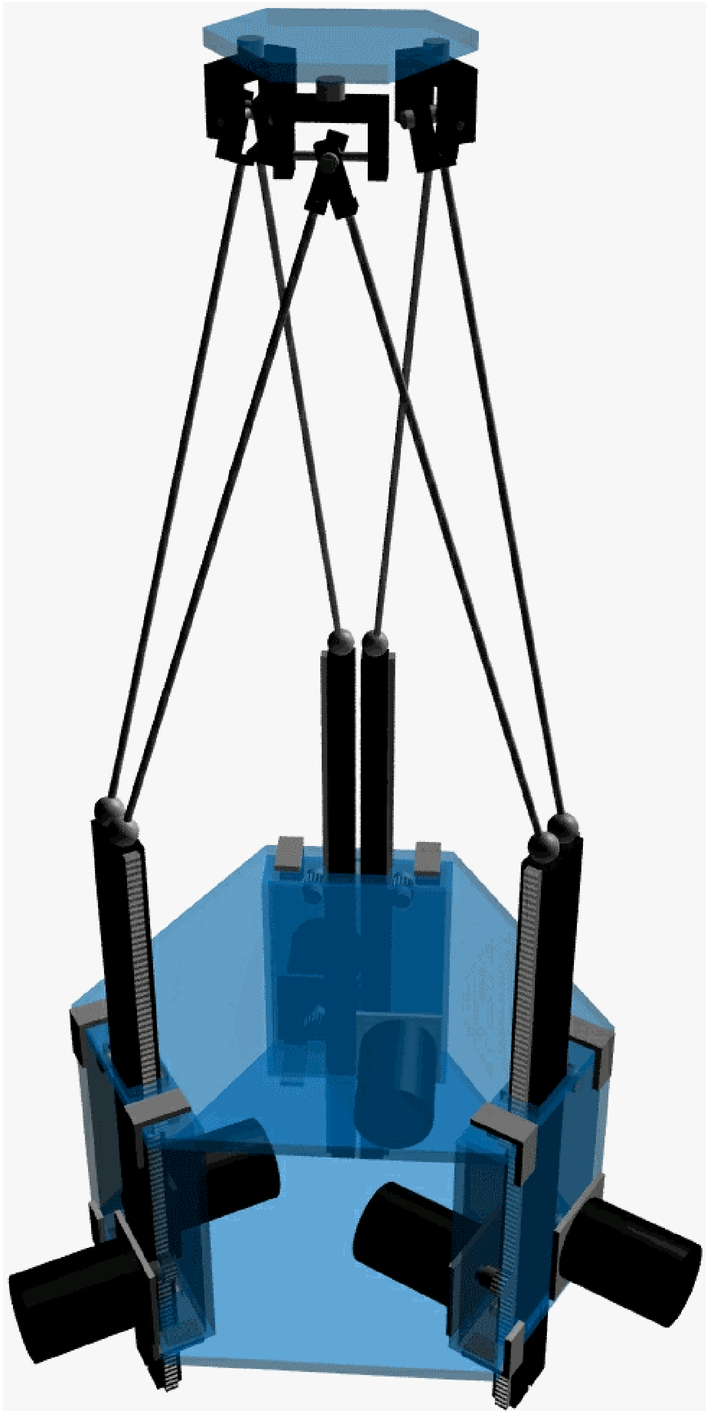


Figure 12.5-3. Stewart Platform

DATA SHEET 12.5. MONITORING AND SENSING OF CUTTING TOOLS AND MACHINE TOOLS

Developing Critical Technology Parameter	No quantitative parameters are available; a continuing, ongoing program. Thin film sensors (coated with a hard protective layer) can be deposited onto the cutting tool and used to measure the condition of the tool. In machine tools, the sensors are mounted within the mass of the machine tool and measure parameters such as temperature, vibration, and so forth.
Critical Materials	Capacitance gauging, lasers, sensors, and so forth.
Unique Test, Production, Inspection Equipment	Computers and sensors.
Unique Software	Unique algorithms to monitor cutting tool or machine tool condition.
Technical Issues	Need for robust sensors for use in hostile machine shop environment.
Major Commercial Applications	General machine tool operation.
Affordability	Cutting time is the criterion used by most manufacturers for tool life. With sensors mounted on, or in, the tools to measure parameters such as force (radial and thrust) and torque, a more accurate determination of tool life and condition is possible.

RATIONALE

Cutting time is the criterion used by most manufacturers for tool life. However, cutting tools experience not only some wear (often uneven) during most of the cutting period, but also chipping or breaking. With sensors mounted on, or in, the tools to measure parameters such as force (radial and thrust) and torque, it should be possible to obtain a more accurate determination of tool life and/or damage to optimize the cutting process. This would result in cost savings to the machine shop operation—in avoiding unnecessary tool changes and in minimizing damaged product. Thus, this is an affordability issue.

The normal operation of a machine tool generates heat and vibration within the mass of the machine tool. Both can affect the positioning accuracy and cut of the tool. Accurate monitoring of these parameters, coupled with a feedback mechanism, can minimize most of the heat and vibration effects. This should improve the machine reliability and maintainability.

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	France	●●	Germany	●●●	Greece	●●
Hungary	●	Italy	●●	Japan	●●●	Spain	●●●
Switzerland	●●	UK	●●	United States	●●●		

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Extensive research is being conducted in machine and tool monitoring worldwide. An international consortium of companies representing seven countries, IMS-SIMON, is directly involved in such research.

In North America, the following organizations have active programs in machine/tool monitoring: NIST, LLNL, ORNL, the University of Michigan, the University of Illinois, the University of Maryland, Montronix, Ingersoll Milling Machine Company, and TPS in the United States and the National Research Council Canada, University of British Columbia, the University of Victoria, and Memex Electronics in Canada.

In Europe, the following organizations have active programs in machine/tool monitoring: the Technische Hochschule Aachen, the University of Passau, the Fraunhofer Institute, Robert Bosch, Prometec, WZL Research Institute, and Laser Zentrum Hannover in Germany; Tekniker, Soraluce, Ikerlan, Danobat, and Ideko in Spain; Giat and Objectif in France; Grau and Epsilon in Greece; Fidia and TXT in Italy; Leeds University, Birmingham University, and Nottingham Trent University in the United Kingdom; Kistler Instrumente and Hindel Gears in Switzerland; and the Hungarian Academy of Sciences in Hungary.

In Asia, the following organizations have active programs in machine/tool monitoring: Nagoya University, Kobe University, Keio University, Mitsubishi Materials Research Center, Hitachi Seiki Machine Tool Company, and NTN Company in Japan.

DATA SHEET 12.5 MICROMACHINES

Developing Critical Technology Parameter	No quantitative parameters are available. However, the general concept is to build extremely small machines (using miniaturized machine tools) that can perform the same tasks, albeit on a miniature scale, as conventional machines.
Critical Materials	Material of end product.
Unique Test, Production, Inspection Equipment	Machine tools or lasers capable of producing the micromachines.
Unique Software	None identified.
Technical Issues	Difficulty in producing miniature micromachines with existing technology.
Major Commercial Applications	Overall applications are unknown. Initial interest includes invasive medical devices and very small items, such as mini-gyroscopes, micromotors, pumps, and robots.
Affordability	Not an affordability issue.

RATIONALE

Micromachines are extremely small and comprise minute (millimeter range) functional elements that are highly sophisticated and are capable of performing complicated tasks. The concept of micromachines is similar to that of MEMS technology (i.e., manufacture devices that are extremely small, allowing continued miniaturization of hardware, with the many benefits associated with miniaturization). Military applications could include miniature gyroscopes, and so forth.

WORLDWIDE TECHNOLOGY ASSESSMENT

Japan ●●●● United States ●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in this field has been conducted primarily in Japan in the following organizations: the Micromachine Center, the Mechanical Engineering Laboratory, the Electrotechnical Laboratory, and the National Research Laboratory of Metrology, the University of Tokyo, Nagoya University, the Tokyo Institute of Technology, DENSO, Toyota Technological Institute, Fujikura Ltd., Mitsubishi, Olympus, Sanyo, Toshiba, and Murata. In the United States, Sandia National Laboratories and SRI International have programs.

DATA SHEET 12.5. MICROELECTROMECHANICAL SYSTEMS (MEMS)

Developing Critical Technology Parameter	No quantitative parameters are available. However, the general concept is to build extremely small machines (devices) that can perform the same tasks, albeit on a miniature scale, as conventional machines. In short, MEMS devices should be smaller, less expensive, and more reliable than more conventional devices.
Critical Materials	Silicon wafers; other materials used in microelectronics fabrication industry.
Unique Test, Production, Inspection Equipment	Standard semiconductor manufacturing equipment, including photolithographic equipment, dry etchers, deposition equipment, and systems for reactive ion etching, LIGA, wafer-to-wafer bonding, and so forth.
Unique Software	None identified.
Technical Issues	MEMS is dependent on the technologies associated with semiconductor fabrication. Improvements in MEMS devices is dependent not only on designs, but on improvements in the fabrication techniques (e.g., advanced etching techniques), which can result in higher aspect ratio structures, improved packaging materials and techniques, and improved CAD.
Major Commercial Applications	Unlimited applications. Present uses include accelerometers for airbag deployment in automobiles; micropressure sensors, medical microfluidic systems; micromirrors for projectors; nozzles for inkjet printers; and fluid flow sensors.
Affordability	MEMS fabrication is less costly than the fabrication of traditional components. MEMS-based systems often have improved performance or reduced size and weight, which leads to further savings.

RATIONALE

MEMS are micron-scale devices that integrate novel sensing and actuation functions with traditional microelectronics-based data processing and control systems. MEMS are unique because they combine mechanical or structural elements, such as accelerometers and micromirrors, with electronic elements, such as microprocessors and radio frequency transmitters. An example is the wristwatch-size MEMS-based system developed for the Marine Corps that allows an individual soldier to monitor battlefield conditions and transmit the information to others in his unit or back to his command post. Potential military applications include accelerometers for controlling military and aerospace systems; inertial measurement systems for munitions, platforms, and personal navigation; unattended sensors for asset tracking and security surveillance; integrated fluidic systems; weapons safing, arming, and fuzing; mass data storage; integrated micro-optomechanical components; and so forth. MEMS are also being developed for use in chemically and thermally harsh environments, such as jet engines, using materials other than silicon. MEMS are likely to become a pervasive technology in defense and commercial arenas for a variety of applications (presently an industry standard for pressure sensors and accelerometers). The benefits include reduced cost, size, and weight and, in some cases, enhanced performance. Figures 12.5-4 and 12.5-5 are representative of the structures being fabricated.

Information on defense applications of MEMS is available at www.ida.org/mems.

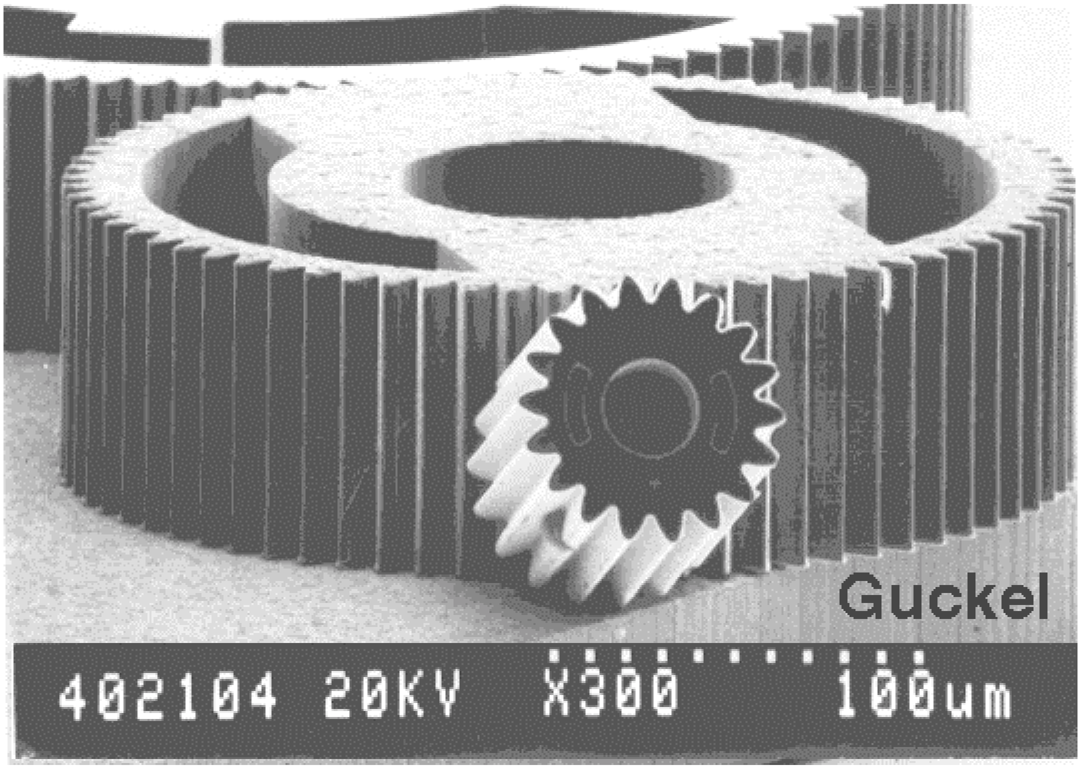


Figure 12.5-4. MEMS Gear

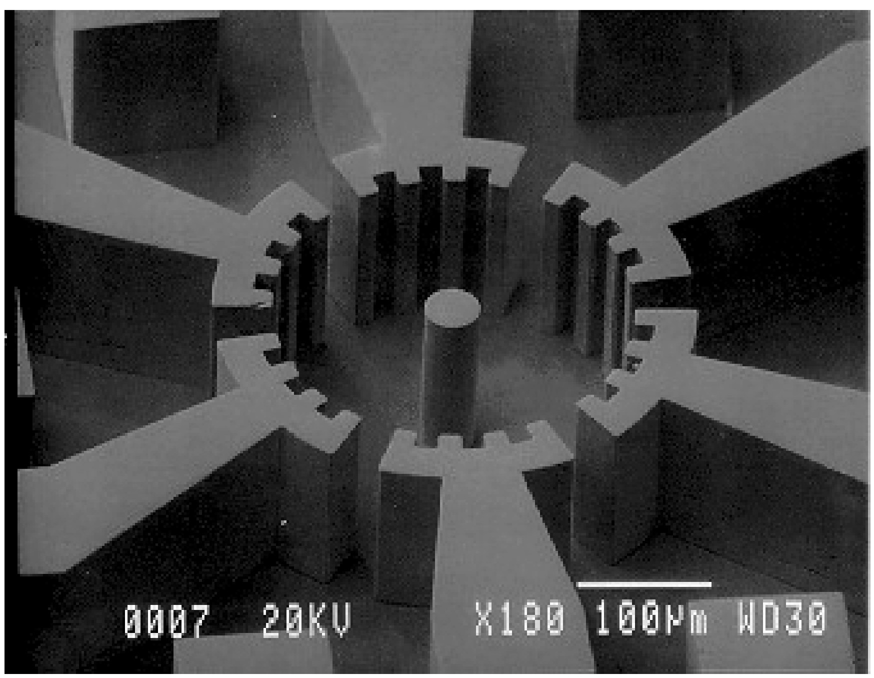


Figure 12.5-5. MEMS Motor

WORLDWIDE TECHNOLOGY ASSESSMENT

Canada	●●	China	●	France	●●	Germany	●●●
India	●	Japan	●●●	Korea	●●	Netherlands	●●
Norway	●●	Sweden	●●	Switzerland	●●	UK	●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in MEMS is global. Leaders are the United States, Germany, and Japan. Extensive programs also exist in Canada, Korea, France, the Netherlands, Norway, and Switzerland. Preliminary efforts are starting in China and India. Information on MEMS suppliers is available at http://mems.isi.edu/mems/yp/list-all-company.html.

Key industrial, government, and university programs include:

United States

Analog Devices
Boeing
Carnegie Mellon University
Case Western Reserve University
Draper Labs
Honeywell
JPL
MIT
Microelectronics Center of North Carolina (MCNC) University
NIST
Raytheon
Sandia National Laboratories
Stanford University
University of California at Berkeley
University of California at Los Angeles
University of Michigan

Canada

University of Alberta

China

Fudan University
Hong Kong University of Science and Technology

France

CNRS
Institute de Microtechniques de France-Comte
LETI
Université de France-Conte

Germany

Bartels Mikrotechnik
Fraunhofer Institute
Institute of Microtechnology Mainz
IVAM NRW e.V.
Karlsruhe Research Center
Max Planck Institute
Mikrosystemtechnik
Technische Universität-Berlin

India

Indian Institute of Science, Bangalore

Japan

Denso Corporation
Hitachi Corporation
Micromachine Center (Tokyo)
Nippondenso Research Laboratories
NTT
Seiko
Toyota Central Research and Development Laboratory
University of Tokyo and Tohoku University
Yokogawa Electric Corporation

Korea

Samsung Advanced Institute of Technology
Seoul National University

The Netherlands

3T
MESA Research Institute
Twente MicroProducts
University of Twente

Norway

SensoNor
SINTEF Electronics and Cybernetics

Sweden

Industrial Microelectronics Center
Royal Institute of Technology
Uppsala University

Switzerland

CSEM Microsystems
Ecole Polytetch Federale de Lausanne
ETH-Zurich
University of Neuchatel

The United Kingdom

Applied Microengineering, Ltd.
Lammerholm Flemming
University of Sheffield
University of Southampton
University of Warwick

DATA SHEET 12.5. FIRST PART CORRECT (OR VALID)

Developing Critical Technology Parameter	Ability to take complicated engineering designs from design to manufacturing and have the end product meet all specifications the first time.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Computers and normal manufacturing equipment.
Unique Software	Computer-aided design/computer-aided manufacturing/computer-aided engineering (CAD/CAM/CAE) programs.
Technical Issues	Most steps in the evolution of the final product (can) contribute to the problem: CAD, CAE, CAM thermal problems in machine, feed speed, strain on spindle, and so forth.
Major Commercial Applications	All manufacturing operations; however, the most important area would be for items manufactured in small volumes.
Affordability	In small-volume applications, each part that does not meet specification is a significant part of the overall cost.

RATIONALE

This is a significant affordability issue for all products made in small volumes. As the number of required parts decreases, each part that does not meet specifications results in a significant increase in the cost of the delivered product. This is particularly important for job shops that produce small-quantity products and for companies supplying replacement parts. This latter situation is critical to DOE's nuclear program and to the U.S. military. In the former, DOE only has a need only for replacement parts for aging weapons. In the latter, DoD constantly needs replacement parts for hardware that uses technologies no longer in normal commercial production.

WORLDWIDE TECHNOLOGY ASSESSMENT

France	●●●	Germany	●●●	Japan	●●●●	Netherlands	●
Singapore	●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Research in "first time right" is primarily carried out in manufacturing facilities, whether engaged in large-scale production or small-scale production. The former would include large industrial manufactures and organizations, regardless of their size, that had significant interest in producing one-of-a-kind product (e.g., replacement parts in the nuclear arena). The latter would include small job shops that customarily produce small numbers of product. No effort has been made to list companies in the latter category because numbers would be too great.

In the United States, the following organizations can only be considered a sampling of the institutions involved in efforts to produce "first time right" product: ORNL, LLNL, Sandia National Laboratories, National Center for Excellence in Metalworking, Cornell University, AT&T, Milicron, Inc., Eastman Kodak, General Electric, IBM, United Technologies Research Center, Ford Motor Company, General Motors Corporation, and Chrysler-Daimler.

In Europe, the following organizations can be assumed to have research programs: CNRS, Renault, Peugeot, and Citroen in France; Rohm & Haas, Siemens, Daimler-Benz, BMW, and Volkswagen in Germany; and Delft University of Technology in the Netherlands.

In Asia, the following organizations can be assumed to have research programs: Japan Synthetic Rubber, Furakawa Electric Co., Mitsubishi, Nippon Steel, Nissan Motors, Toyota Motors, and Honda Motors in Japan and Pioneer Die-Casting in Singapore.

12.6—ROBOTICS

Highlights

- Advanced sea, air, and land robots will carry out a wide range of military operations, ranging from chemical and biological warfare (CBW) detection and reconnaissance to mine detection.
- The development of fractal, self-duplicating, self-repairing robots would be a significant breakthrough in the design of military hardware.

OVERVIEW

This section covers the developing technology for advanced battlefield robots, encompassing robots for land, sea, and air. Possible robots include:

- **Ground robots.** Although these robots could be designed for many different applications, early planning has addressed the fields of cameras, sensors, or equipment for gathering and disseminating information.
- **Seaborne robots that resemble jet skis.** These robots can be equipped with a various types of equipment, including underwater cameras, laser scanners, night vision equipment, radar, and so forth.
- **Micro and mini air vehicles (MAVs).** Proposed designs of these pilotless machines vary from micro (smaller than 6 in.) to extremely small (8- to 10-in. size) to moderate (on the order of 3- to 5-ft size). Initial plans would be for the craft to carry some type of sensor, although they could also carry small amounts of explosives.
- **Fractal shape-changing robots.** These robots can, theoretically, change shape, replicate, self-repair, and perform a wide variety of military tasks.

Considerable effort is being expended to develop MAVs that can serve as observation planes or sensors for WMD. Such a concept will most probably make use of MEMS technology. To be effective, the MAVs would require sensors and transmitters. Classical sensor development has been a major part of MEMS research, and engineers at MIT have developed a TV camera on a chip. Some of the major obstacles are the aerodynamics of such a small plane and the weight requirements of sensors, transmitters, and propellant systems.

The fractal shape-changing robots are a form of nanotechnology and are still in the conceptual stage. However, interest has been increasing since the inventor was awarded the 1996 European Invention Competition of Monaco. In addition, statements by personnel at British Telecomm predict, in their "1997 Technology Calendar," that early forms of these robots are most likely to exist by 2005. The concept of self-replication is a basic tenet of nanotechnology, whether one considers classic nanotechnology or molecular nanotechnology. The goals of nanotechnology are low cost, molecular precision, and flexibility. Some authors believe these can only be reached with the development of self-replicating objects.

RATIONALE

Robots are indispensable in many hazardous military operations, including the handling of munitions, operating in highly radioactive or electromagnetic pulse (EMP) environments, and performing tasks in space. The use of robots in these applications extends the military capability much further than that which could be accomplished with "protected" humans. The robots addressed in this "developing technology" volume are extensions of the existing robotic technologies. The more typical sea, air, and land robots addressed are significant advances over what the military presently fields. They should extend the observation/reconnaissance capabilities of existing technologies not only because of their additional capabilities, but because their size should limit their "detectability" and extend their ability to gain access.

The eventual applications of the less conventional fractal shape-changing robots are more difficult to quantify. Theory says that they will be very small, almost indestructible (since they are self-repairing); can change shape, if necessary, to gain access to small or odd-shaped openings; and can carry out most operations presently performed by soldiers in the field.

WORLDWIDE TECHNOLOGY ASSESSMENT (See Figure 12.6-1)

Robotic research is a major international endeavor. Although most research is carried out by commercial/ university laboratories and most is directed toward civil applications, much of the technology is also applicable to military applications. Military applications include land-based robots (many designed for mine clearing), undersea robots, and unmanned aerial vehicles (UAVs).

Country	Land Robotics	Sea Robotics	Unmanned Air Vehicles	Fractal Robots
Australia		●●		
Belgium	●			
France	●●●●	●●●		
Germany	●●●●	●●●●	●●	
Italy		●		
Japan	●●●●	●●●●		
Russia			●	
Singapore		●		
South Africa	●			
Sweden		●		
UK		●●●●	●●	●●
United States	●●●●	●●●●	●●●●	●●

Legend:
Capability in technology elements ●●●● most ●●● many ●● some ● at least one

Figure 12.6.-1. Robotics Systems WTA Summary

LIST OF TECHNOLOGY DATA SHEETS
12.6. ROBOTICS

DATA SHEET 12.6. BATTLEFIELD ROBOTS

Developing Critical Technology Parameter	Perform reconnaissance, mine clearing, material handling, target identification, and CBW detection.
Critical Materials	Sensors.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control action of the robot.
Technical Issues	Reliability, cost, use in inclement weather, and ability to traverse uneven terrain.
Major Commercial Applications	Law enforcement.
Affordability	Not an affordability issue in dollars and cents matters but definitely an affordability issue in human life and safety matters.

RATIONALE

Successful military missions are characterized by rapid response, minimal casualties, and minimal hardware cost. Of particular risk to military personnel are intelligence gathering, surveillance, and reconnaissance. Battlefield robots should be able to perform many of these tasks efficiently, at minimum cost, and with significantly reduced threat to personnel. Figure 12.6-2 shows a battlefield robot developed for reconnaissance.

Research on battlefield robotics should result in products that can be outfitted with mine-detection equipment (mine clearing), video and IR-sensing systems (surveillance and reconnaissance), sensors for chemical and biological weapons, or sensors for nuclear radiation. Computers and telecommunications equipment are critical components of all these robots.

Research robots that use either conventional tire/wheel systems or Archimedes screw-type systems are being developed. The latter may result in more precise directional control, although it may be more expensive than the more conventional approaches.

Potential military applications include counterterrorism, surveillance, reconnaissance, intrusion detection, and mine detection (removal).

WORLDWIDE TECHNOLOGY ASSESSMENT

Belgium	●	Canada	●	France	●●●	Germany	●●●
Italy	●	Japan	●●●●	Russia	●	Spain	●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Robotic research is a major international endeavor. Although much of the research is conducted by industrial/university laboratories and is directed toward civil applications, much of the technology is applicable to military applications. The United States, France, Germany, and Japan appear to be the most heavily involved, although other countries have active, meaningful programs. Since the number of organizations involved in robotics is so large, the following is only a sampling.

In the United States, the following organizations are representative of the effort in robotics: Space and Naval Warfare Systems Command (SPAWAR), ARL, NASA, JPL, LLNL, Sandia National Laboratories, ORNL,

Figure 12.6-2. Reconnaissance Land Robot

Omnitech, Philips Labs, INEL, MIT, Georgia Tech, Virginia Tech, Caltech, the University of Wisconsin, the University of Maryland, Stanford University, Carnegie Mellon University, the University of Rochester, and Cornell University.

In Europe, the following organizations have research programs: ENSEA-ETIS, LIFIA, LAAS-CNRS, Ecole des Mines de Paris, ITMI-Aptor, Giat, Dassault Electronique, Sagem, the Paris Robotics Laboratory, and the Complex Systems Group in France; the Technical University of Munich, the University of Würzburg, the Technical University of Darmstadt, Dornier, and the Institute of Automatic Contro Engineering in Germany; Cambridge University, the University of Birmingham, the University of Surrey, and the University of Newcastle in the United Kingdom; CELL Robotics in Belgium; CNR-IESS in Italy; the University of Sevilla in Spain; and the University of Amsterdam in the Netherlands.

In Asia, the following organizations have research programs: Nagoya University, Meijo University, University of Tsukuba, University of Tokyo, Osaka Electro-Com, Wasada, Toyo, Riken Corporation, Hitachi, Ltd., and Mitsubishi in Japan.

The Defense Research Establishment in Canada and the Moscow Bauman State Technical University in Russia are also active in land-based robotics.

DATA SHEET 12.6. UNDERSEA ROBOTS

Developing Critical Technology Parameter	Perform reconnaissance, on water surface and underwater, including cameras (visual), laser scanning, night vision, and so forth.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control action of the robot.
Technical Issues	Reliability, cost, use in inclement weather, ability to operate in rough seas, and acoustic transmission between the robot and a "mother ship."
Major Commercial Applications	Underwater research, shipwreck investigations, oil and mineral exploration.
Affordability	Not an affordability issue.

RATIONALE

Undersea robots will extend operational range of robotic technology, using low-visibility, expendable vehicles. The U.S. Navy has already placed several robots into service, for reconnaissance and anti-mine tasks. The use of small robots (6 to 10 ft in length) offers a significant technology to the Navy, at costs considerably less than those encountered using larger, more expensive vessels. In addition, it allows operation at considerable depths and in mine-infested waters—environments that pose significant risks to personnel using more conventional techniques. Figure 12.6-3 shows a robot developed for underwater reconnaissance.

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	France	●●	Germany	●●	Italy	●
Japan	●●●	Singapore	●	Sweden	●	UK	●●●
United States	●●●●						

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Extensive research in underwater robots is being conducted in most industrialized countries that have significant shorelines, are involved in oil exploration, or are active in ocean salvage. The United States, Japan, and the United Kingdom appear to have the most extensive programs.

In the United States, the following organizations have extensive research programs: SPAWAR, the Naval Postgraduate School, the Naval Undersea Warfare Center, Woods Hole Oceanographic Center, the Autonomous Undersea Systems Institute, Texas A&M University, and MIT.

In Europe, the following organizations have programs: DERA, CMPT, Slingsby, Shell-UK Exploration and Production, Heriot-Watt University, the University of Essex, and Cranfield University in the United Kingdom; the Institute Français de Recherche pour l'Exploitation de Mer, INRIA, and the Institute Nationale de Recherche et en Automatique in France; the Technical University of Hamburg, the University of Hannover, and the Forschungszentrum Informationstechnik GmbH in Germany; CNR-IAN in Italy; and the University of Uppsala in Sweden.

In Asia, the following organizations have programs: JAMSTAC; University of Tokyo, Meiji University, Tokai University, the Tokyo Institute of Technology, and KDD in Japan; the Australian National University in Australia; and the Nangyang Technological University in Singapore.

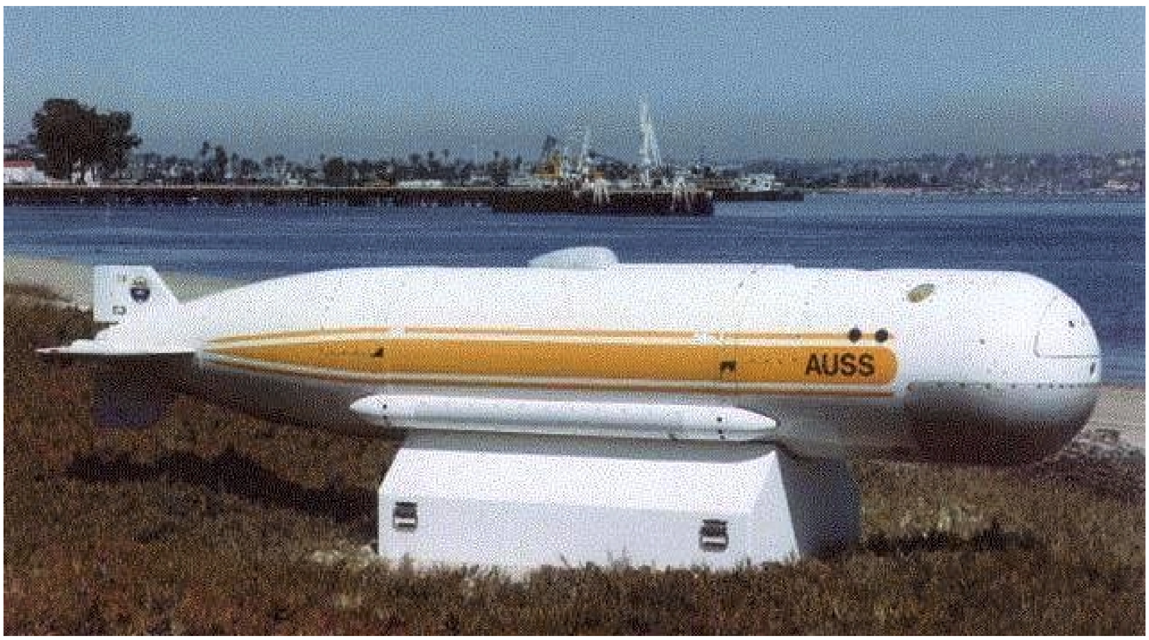


Figure 12.6-3. Underwater Robot

DATA SHEET 12.6. MICRO AIR VEHICLES (MAVs)

Developing Critical Technology Parameter	Perform reconnaissance, target identification, and CBW detection.
Critical Materials	None identified.
Unique Test, Production, Inspection Equipment	Standard machine tools, computers, and so forth.
Unique Software	Software algorithms to control the robot's action.
Technical Issues	Aerodynamics at low speed and low altitude, power (batteries or solar), propulsion system, length of flight, cost, use in inclement weather, and low observability.
Major Commercial Applications	Possible application in agriculture (crop studies), archeology (study of terrain), crowd control, and search and rescue.
Affordability	MAV should be considerably less expensive than conventional drones. In addition, the use of MAVs would minimize the danger to personnel.

RATIONALE

MAVs hold great promise as flight platforms for tactical optical, acoustic, electronic, and chemical/biological sensors for operation in hazardous areas. MAVs should allow brigade commanders to ascertain enemy strength, the type of terrain, targeting information, and the presence of chemical/biological weapons before engaging the enemy and without exposing the military personnel to the dangers of such tasks.

MAVs should be small enough to be handled in the field by one or two soldiers. They should have the capability of flying for up to an hour and possessing either sensors or cameras and telecommunication equipment. Figure 12.6-4 shows a conventional UAV being developed for reconnaissance duties and an extremely small MAV being developed for a wide range of potential applications. Figure 12.6-5 is an example of a less conventional approach to MAVs, one using the concept of "flapping wings."

WORLDWIDE TECHNOLOGY ASSESSMENT

Australia	●	Canada	●	Germany	●●	Russia	●
UK	●●	United States	●●●●				

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

Extensive research is being conducted on MAVs in the United States, with considerable funding from DARPA. Germany and the United Kingdom also have extensive programs, with some effort also existing in Australia, Canada, and Russia.

In the United States, the following organizations have research programs: NASA/Dryden, NRL, SPAWAR, JPL, Sandia National Laboratories, Georgia Tech, MIT, Caltech, Vanderbilt University, the University of Florida, the University of Washington, Teledyne Ryan Aeronautics, TRW, Inc., Aerovironment, Lockheed-Martin, Lutronix Corporation, SRI International, General Atomics, Raytheon, and Carolina Unmanned Vehicles.

In Europe, the following organizations are active: Bosch Aerospace, Stenne Flugzeugbau, Daimler-Benz, and STN Atlas Electronik in Germany and DERA-Malvern, the University of Cranfield, the University of Southampton, the University of Bristol, Nortel Technology, and Cranfield Aerospace, Ltd., in the United Kingdom.

Others with programs include the University of Sydney in Australia; Bombardier Aerospace in Canada; and the St. Petersburg Institute for Interferometrics and Automation in Russia.

(a) More Conventional Reconnaissance UAV

(b) Less Conventional MAV

Figure 12.6-4. UAVs

Figure 12.6-5. UAV "Flapping Wings" Approach, as Researched at Georgia Tech

DATA SHEET 12.6. FRACTAL SELF-SHAPING ROBOTS

Developing Critical Technology Parameter	Extremely small (nanotechnology approach), shape-changing, self-repairing cubes.
Critical Materials	None identified, as yet.
Unique Test, Production, Inspection Equipment	Computers.
Unique Software	Software algorithms to control action of the robot.
Technical Issues	None identified, as yet.
Major Commercial Applications	Potential applications include medical technology, bridge building, space technology, and so forth.
Affordability	Not affordability issue.

RATIONALE

A fractal is a shape that, when one looks at a small part of it, has similar (but not necessarily identical) appearance to the full shape.

Fractal shape-changing robots presently make use of large numbers of small cubes, each containing a computer chip, programmed to perform specific functions. These functions can include movement, laterally or vertically, and can effect a change in the shape of the final structure. Proposed military applications include mine clearing and weapons or aircraft that have the ability to self-repair damage caused by enemy action. Figure 12.6-5 shows examples of fractal robots.

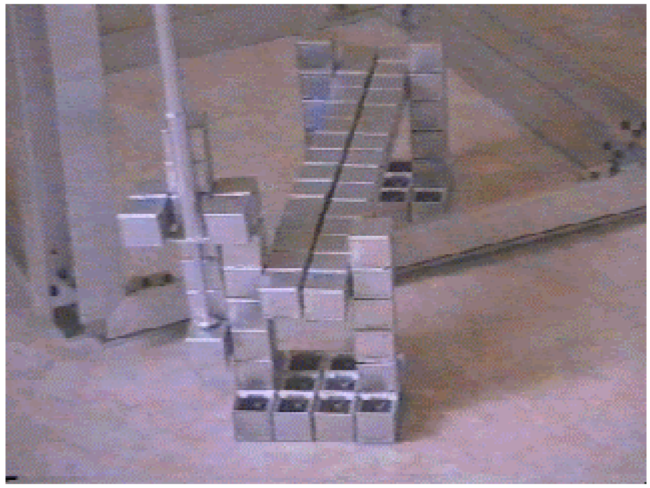
Futurists at British Telecom have predicted the commercial/military use of these robots in the 2015 to 2020 time frame.

WORLDWIDE TECHNOLOGY ASSESSMENT

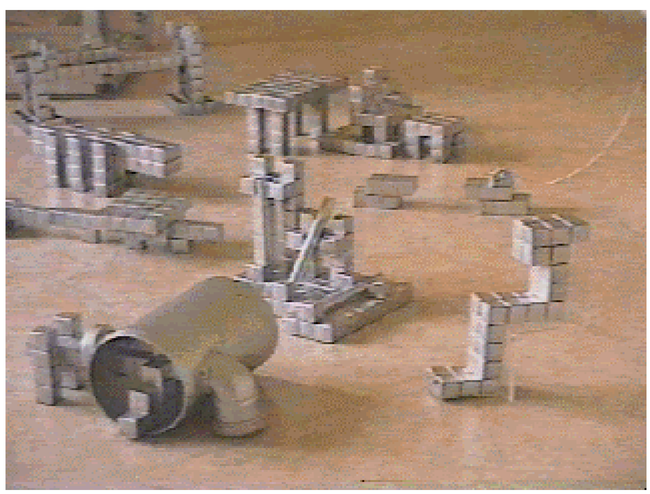
UK ●● United States ●●●

Legend: Extensive R&D ●●●● Significant R&D ●●● Moderate R&D ●● Limited R&D ●

At the present time, research in fractal robots is quite limited, with efforts at NASA, Rice University, Nanotechnology Development Corporation, and the Hollotron Corporation in the United States and at Robodyne Cybernetics in the United Kingdom.



(a) Robotic Demonstration of Bridge Building



(b) Various Examples of Fractal Robot Structures

Figure 12.6-5. Fractal Robots

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